THE PHYSIOLOGY OF VISION

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WITH SPECIAL REFERENCE TO COLOUR BLINDNESS

BY

F. W. EDRIDGE-GREEN

M.D., F.R.C.S.

Oculist London Pensions Boards ; late Chairman Ophthalmic Board, Central London Medical Boards, National Service; late Member International Code of Signals Committee; late Hunterian Professor of the Royal College of Surgeons, etc. ; Inventor of Colour Perception Spectrometer, Colour Perception Lantern the Official Test of the Navy ; and Bead Test, the Test of the National Service

LONDON

G. BELL AND SONS, LTD.

YORK HOUSE, PORTUGAL ST., KINGSWAY, W.C. 2

1920

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PREFACE

This book is the result of numerous researches on vision and colour-vision, the principal original papers of which are given at the end of the volume, and present the subject in a new aspect. It will be noticed that each section of the subject has been given from the point of view of new facts apart from any theory and so is available for an explanation on any theory.

The subjects of vision and colour-vision have been viewed too much from the point of view of theory and the primary assumption is made that the theory is true when this can be easily shown not to be the case, as for instance long papers on induction when there is no induction and the classification of colour blindness as red blindness, green blindness, etc., when this classification is so meaningless that a man may be classified by one observer as a case of complete red blindness and by another as a case of complete green blindness.

It is probable that it is for this reason that it is so extraordinarily difficult to establish a new fact. It took me twenty years to establish such simple facts as

that certain colour-blind men can pass the wool test and that when a certain portion of the spectrum is isolated it appears monochromatic.

I must, therefore, express my indebtedness to those who have examined the facts and especially to Professors Starling and Bayliss.

In this book I have attempted to give a simple comprehensive account of form and colour-vision, which will make clear the present state of knowledge on the subject and also indicate the direction in which further research is required. A great deal of the uncertainty which has existed in the past on these matters has been due to the fact that both physicists and physiologists who have written upon this branch of science have had a tendency to accept as the basis of their theories supposed facts, which in a large number of cases have proved not to be facts. The physicists in particular have shown a reluctance to experiment anew. Further, many workers unacquainted with the difficulties of the subject have made use of imperfect apparatus, such as coloured papers, which reflect light corresponding to very ill defined regions of the spectrum, others, as I have often been able to show, have vitiated their experiments by the admission of stray light. Experiments on colour-vision need quite as much care and rigorous definition of conditions as those in any other branch of science. The investigation of the problems of vision requires a knowledge of physics, physiology, ophthalmology, and psychology. A want of knowledge of any of these branches

of science may entirely destroy the value of an experiment or theory.

This book is necessarily very largely concerned with my own work on the subject, extending over the past thirty years. It is gratifying to be able to record that the theories put forward, which met with a good deal of opposition in their inception, are now generally accepted by modern physiologists; I have, nevertheless, been particularly careful to give in all cases the full experimental grounds on which they rest. Anyone who wishes to construct a fresh theory is thus provided with the facts which he must explain, and sufficient details are given to enable him to repeat, if he so desire, my experiments. Where I have rejected the results of former experiments I have given my reasons for believing that the methods were erroneous or that facts had been overlooked. These and other things convince me that a general book on the subject is needed, and I sincerely hope that it may help students who realise the wide imperfections of the old theories but have not the time to hunt through the work scattered in various papers for the information which they require. I believe that the general reader, too, will find much in this branch of science to interest him.

The practical importance of a true understanding of colour-vision is obvious. I will only instance that without a knowledge of the theory of the subject it is impossible to devise tests which will prevent dangerously colour-blind men from being employed as lookouts and

signalmen. As an example of this the old wool test based on the trichromatic theory, in addition to rejecting many normal sighted persons, allows over fifty per cent. of dangerously colour-blind to escape detection. I am not aware of any attempt on the part of the rapidly diminishing number of supporters of the trichromatic theory to explain the above fact and it is therefore an anomaly that the theory should still be taught in physics text books. Those who are interested in the physical aspects of the subject should read the very important paper by Dr. R. A. Houstoun in the *Philosophical Magazine*, Sept., 1919.

The laws of colour contrast are of the utmost utility to designers and kindred craftsmen.

It gives me much pleasure to express here my thanks to Sir Frederick Mott, Profs. A. D. Waller, W. Halliburton, W. M. Bayliss, E. H. Starling, A. W. Porter, Sir Ronald Ross, Dr. A. Lynch, Dr. R. A. Houstoun, Mr. T. H. Bickerton, Dr. E. N. da C. Andrade, Lord Moulton, and many others for the interest which they have taken in my work.

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CHAPTER I.

THE EXCITATION OF THE VISUAL APPARATUS.

We can only have cognisance of the external world as our senses and faculties inform us of its existence. Any defect, either in the sense organ or perceptive centre, by preventing the perception of certain classes of sensations, has the same effect as if the physical stimuli giving rise to the sensations did not exist. It is impossible to explain to a man who has been born blind the nature of sight; he does not feel his loss in the same way as a man who has once been possessed of vision.

The Doctrine of Specific Sense Energy.

Johannes Müller made a great advance in the physiology of the organs of sense when, adopting the views of Bell, he formulated his laws of specific sense energy. He showed that the sensations that we experience of light, colour, sound, heat, etc., are the special properties of the sense organ and its cerebral associations and not a function of the external stimuli which caused those sensations; for instance, the sensation of light which is caused by stimulation of the cerebro-retinal apparatus is a special function of this apparatus, and any

stimulus acting upon the eye can only give rise to a sensation of light when this is conveyed through the optic nerve. Mechanical, thermal, or electrical stimuli applied to the retina or optic nerve give rise, if they produce an effect, to a sensation of light. In the same way any of these stimuli applied to the auditory nerve, if they give rise to any sensation at all, give rise to a sensation of sound. When the same stimulus falls upon two different sense organs, it gives rise in each to the sensation peculiar to that organ; for instance, the rays of the sun falling upon the hand give rise to a sensation of heat through a stimulation of those nerves which cause when stimulated a sensation of heat. It follows from this that sensations only exist in ourselves, and that the sensation only bears a resemblance to the stimulus as a written symbol bears to the thing it describes. Without the eye the world would be in darkness, without the ear in silence.

There are undoubtedly special physical stimuli which give rise to light and sound respectively, but there are closely allied physical stimuli which are not perceived by us at all; for instance, photographs can be taken in a room which appears absolutely dark to us. These photographs by ultra-violet or infra-red light have special characters of their own. This shows that physical stimuli which are not perceived by our senses are capable of doing important work. There are essential physical differences which are not detected by the sense organ; for instance, we cannot distinguish

between polarized and non-polarized light by the eye. In the future, it may be found that some of the physical stimuli causing the sensation of light have very different characters but agree in causing a sensation of light when acting upon the eye.

Those stimuli for which the sense organ is specially constructed are called adequate stimuli, as, for instance, light in the case of the eye and sound of the ear. Other stimuli capable of producing a sensation are called inadequate stimuli.

A corollary which has become attached to that of the specific energy of the senses is that nerve impulses are similar in all nerves, and that, therefore, any differences must exist at the peripheral and central ends of the nerves. There is no evidence for this hypothesis, which seems in the highest degree improbable. There is no evidence to show that a nerve cannot transmit impulses of varying rate and length. We have an example of how this is accomplished in the case of sound by the telephone. It would not be necessary that the impulses should be in the same order of frequency as the physical stimuli causing the impulse, but they might bear some definite relation to them. We know, however, very little at present of the nature of nerve impulses.

We now have to consider how the physical stimuli affect the sense organ, and how the sensations vary with different people.

If we compare a number of persons with regard to their sensations, we find that these differ in a remarkable

manner. For instance, one man will declare that a room which is brilliantly lit up with red lights is absolutely dark; another will declare there is nothing to be heard when a bat or a mouse is screaming; another will state emphatically that there is no difference in taste between pheasant and mutton, or that port and sherry are exactly alike except for colour. There are innumerable varieties and degrees in these differences of sensation. As the sense organ has been developed in the process of evolution to respond to certain physical stimuli, it is probable that the differences found between persons in their capacity of differentiating between the physical stimuli affecting one of their sense organs corresponds to an earlier state in the evolutionary process. Have we any means of ascertaining the lines on which evolution has proceeded? We know that the physical stimuli which affect our sense organs differ in their physical characters, and each set of physical stimuli can be arranged in a series; for instance, the waves causing the sensation of sound can be arranged according to their size from the lowest bass note to the highest treble, or waves which cause the sensation of light from the lowest perceptible red to the highest perceptible violet. We should, therefore, expect that the sense organ would be evolved so that it would discriminate between those physical stimuli which were physically most different. We should also expect that the sense organ would be developed so that the range of sensitiveness to the physical stimuli at the ends of the series

was increased, that is to say that the length of the physical series which affected the sense organ became increased.

The differences found in the varying sensations of different persons fall into two distinct classes—namely, inability to distinguish between physical stimuli occupying neighbouring positions in the physical series, and inability to perceive physical stimuli occupying positions at one or both ends of the physical series. The appearance of a physical series to any person may be called the psycho-physical series for that person. A psycho-physical series is a physical series as it appears to the mind.

A. Physical Series.

A physical series consists of various physical stimuli arranged in a series. For instance, the waves which give rise to the sensation of sound or those giving rise to the sensation of light may be arranged in a series from the largest to the smallest. We also know that the series is continued both above and below the range which is capable of giving rise to a sensation. A physical unit is the smallest conceivable portion of a physical series.

B. Psycho-Physical Series.

A psycho-physical series is a physical series as it appears to the mind. It has a definite commencement, a definite termination and certain definite units. A

spectrum forms an admirable instance of a psycho-physical series. An absolute psycho-physical unit consists of a portion of the psycho-physical series which contains physical units which the observer is incapable of discriminating between, as, for instance, those rays which are included in a portion of a spectrum which appears monochromatic.

Apart from light there are many other physical stimuli which are able to excite a sensation of light. A blow on the eye will cause a sensation of light. Pressure on the eye in the dark will cause a sensation of light in the corresponding part of the field of vision. This has been designated a phosphene. Pressure on the front of the eye will cause the appearance of the star-figure which is described later and the rapidly moving and interlacing currents. Visual sensation has also been caused by electric currents, and by placing the eyes in a magnetic field.

As it is necessary for men and animals to discriminate between adjacent objects, relative difference becomes much more important than actual difference. The physical differences around us are continually changing, and the variations in these physical conditions have to be specially ascertained by physical measurements. The variation in the amount of light falling upon the eye during the day is very considerable, at one period of the day black print may reflect more than twelve times the amount of light reflected by white paper at another period of the day. We are not conscious of

this difference, and the paper looks white and the print black at both periods. If in a dark room a candle be placed so that a shadow is thrown by an opaque object on a screen the shadow is plainly marked and visible. If, however, sunlight be allowed to fall upon the screen as well, or the light from a powerful electric lamp, the shadow becomes invisible and the screen appears uniformly lighted. The perceptible difference in lighting between two adjacent surfaces has been ascertained to be about $\frac{1}{100}$ of the total amount of light in ordinary conditions.

A certain amount of light is necessary before a sensation is evoked, the amount varying according to the state of the eye.

A simple illustration will show how the same physical stimuli falling upon the eye in different conditions may produce opposite results. If a piece of ultramarine blue paper be placed on one side of a photometer and be illuminated by an ordinary incandescent electric lamp, it will be found that it can be exactly matched by a piece of orange-brown paper illuminated by daylight on the other side of the photometer. If the ultramarine blue paper be taken out and examined by the same electric light which was used for the photometer it will be seen that it is a decided blue. Therefore when the blue paper is seen isolated, it appears of a colour complementary to that of its appearance when the surrounding parts of the retina are stimulated by the same light. It will be seen, therefore, that the retina

must be considered as a whole and that the actual effect of any external stimuli upon it must be considered, when all other stimuli are carefully excluded. Nature is not concerned with the fact that one object appears blue and another green, but is concerned with the power of the animal to discriminate between stimuli for the purposes of that animal. Those creatures low in the scale of evolution which possess eyes of a rudimentary character are made aware that there is danger near when a shadow is thrown upon them. As evolution proceeds and each sensory cell is connected with a special nerve cell so does the power of localization in space increase also the power of differentiating between adjacent stimuli. The distance between two cones represents the power of visual acuity. On examining the external surface of the retinae of young monkeys, I found that the cones were much larger and much fewer to the square millimetre than those of an adult man. It would appear from this that man can discriminate between objects which would not be possible to a monkey.

The physiology of vision may be conveniently divided into three sections :

(1) The dioptrics of the eye or the means by which images are formed on the retina.

(2) The means by which the light forming the image on the retina is changed into visual impulses.

(3) The resulting perceptions.

It seems incredible that the cones could be directly stimulated by light. It is so much more probable that

the stimulation of the cones is indirect and photo-chemical. The sensitive ends of the cones are situated in a fluid, which is kept in its place by the external limiting membrane on one side and a corresponding membrane covering the pigment cells on the other.

It is easy to see, therefore, that if this fluid were photo-chemical, we have a ready explanation of the formation of visual impulses, by the stimulation of the cones by the products of the photo-chemical decomposition of this fluid. In the sensitive layer of the retina there are not only cones but rods which are found distributed round the cones except in the fovea. These rods contain a photo-chemical substance, the visual purple. There is, therefore, a substance present which is able to sensitise the fluid round the cones by diffusing into it. This view explains all the ordinary phenomena of vision, including a large number of facts which were previously inexplicable. There is also, as stated by Nagel,[1] not a single fact pointing to the view that the rods are percipient elements. This is the only theory which will explain why there is no qualitative difference between the foveal and para-foveal regions. It also explains the fact that an after-image can change its relative place in the visual field.

[1] *Physiol. des Menschen*, vol. iii. p. 107.

CHAPTER II.

SPECIAL POINTS IN THE ANATOMY OF THE RETINA.

The retina is the membrane which contains the expansion of the optic nerve: it diminishes in thickness from behind forwards, being thickest, about ·4 mm. in the region of the yellow spot, about half that thickness in the equator and about a fourth at the ora serrata or indented anterior portion.

The Layer of Rods and Cones.

The elements which compose this layer are of two kinds, called from their shape rods and cones. Each consists of an outer and inner segment. The rods are about ·06 mm. long and ·002 mm. in diameter. The cones are about ·035 mm. long and about ·006 mm. in diameter.

The outer segments of the rods are imbedded in the pigment cells of the hexagonal layer. Krause has estimated that there are seven millions of cones and 130 millions of rods in the human retina. Sulzer finds only about half this number of each. Sulzer estimates the number of fibres in the optic nerve as about half a

million. It will be seen, therefore, that even if the cones alone be the terminal percipient elements, in the peripheral parts of the retina many cones must be connected with a single nerve fibre.

The outer segments of the rods contain a rose-coloured substance, the visual purple.

The Macula Lutea and Fovea.

This is the most important part of the retina, and differs considerably in structure from the remainder.

The yellow spot is so called on account of the yellow colouring matter which pervades the four or five inner layers.

Gullstrand is of opinion that the yellow colour of the yellow spot is due to a post-mortem change. Apart from the evidence of the pigment which can be obtained during life, I have frequently seen the yellow spot bright yellow in the retinae of monkeys examined immediately after death.

It is somewhat elliptical in shape, and measures about 2 mm. in diameter. The long diameter of the ellipse is horizontal. In the centre of the yellow spot is a small pit, the fovea centralis, which measured in a retina I examined about ·5 mm. The bottom of the pit I found to measure about ·1 mm. Only cones are to be found in the fovea, and they are much longer and thinner than in other parts of the retina. This particularly applies to the outer segments, which thus present a larger surface for photo-chemical stimulation. The

other layers of the retina are much thinner at the fovea than elsewhere, though their thickness gradually increases until in the outer parts of the yellow spot the retina is at its thickest. The layer of ganglion cells is especially thickened at the edge of the fovea. The nerve fibre layer disappears as a distinct layer at the edge of the fovea, the fibres joining the central processes of the

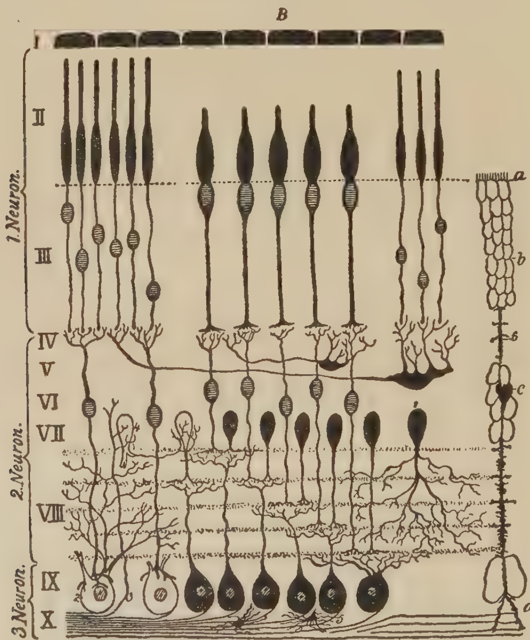


Fig. 1.—Schema of Structure of Human Retina (Greef).

ganglion cells. As the line of the pigment cells remains level and the cones are much longer, the external limiting membrane dips in and thus forms an external fovea. This I found to be ·3 mm. in size in the specimen I examined.

The intervals between the rods and cones and the hexagonal pigment cells are only partially filled by the processes of the latter, the remainder is filled by a liquid into which the visual purple diffuses. There is in the embryo a distinct space between the hexagonal pigment cells and the remainder of the retina. This is filled with fluid, and is the remains of the cavity of the primary optic vesicle.

I find four depressions or canals which lead into the larger depression of the external fovea. These canals appear to have smaller branches, and serve to conduct the visual purple into the part of most acute vision. In certain conditions where there is obstruction of the outflow at the back of the eye these canals form a star figure. The same star figure can be seen entoptically.

The space between the rods and the cones is in direct communication with the lymphatics of the optic nerve, and this is probably how the waste products escape. Schwalbe has shown that this space may be filled by injecting coloured fluid under the sheath which the optic nerve derives from the pia mater.

An examination of the accompanying figure shows the difference in the connections of the rods and cones with the ganglion cells. It will be noticed that whilst that of the cones is direct, the rods terminate in rounded knobs, many of which are connected with one ganglion cell. Transverse cells also connect groups of rods. It

will be seen that for purposes of location in space the rods appear to have a very unsatisfactory anatomical arrangement, any satisfactory method of discrimination appearing impossible on this formation. If, however, the anatomical structure be regarded from the point of view of the distribution of the visual purple, it is exactly what we should expect.

CHAPTER III

THE DIOPTRICS OF THE EYE.

The dioptric portion of the eye is an optical apparatus constructed so that a correct image of an external object may be formed on the retina. It is similar to a camera obscura, and consists of a number of approximately spherical surfaces approximately centred round an optic axis and separated by various media. It has not been finally settled whether the optic axis passes through the fovea, according to some observers it does, whilst others state that it falls a little to one side of it.

Rays of light falling upon the eye and subsequently impinging upon the retina have to traverse in succession the anterior surface of the cornea, the substance of the cornea, the posterior surface of the cornea, the aqueous humour, the anterior portion of the capsule of the lens, the anterior surface of the lens, the various layers of the lens, each of which has a different refractive index, the posterior surface of the lens, the posterior portion of the capsule of the lens and the vitreous humour. It will be seen, therefore, that excluding the capsule of the lens, the rays of light have to traverse four surfaces separated

by five media: the four surfaces being—the anterior surface of the cornea, the posterior surface of the cornea, the anterior surface of the lens and the posterior surface of the lens. The five media are—air, the substance of the cornea, the aqueous humour, the substance of the lens and the vitreous humour.

This optical system can be simplified still further and reduced to three curved surfaces and four media. When rays are refracted by a medium bordered by two spherical surfaces which are concentric to each other the medium and the posterior surface may be ignored and the rays may be considered as passing directly from the anterior surface into the second medium. As the posterior surface of the cornea is approximately concentric with the anterior surface, the substance of the cornea and its posterior surface may be neglected.

It has been shown mathematically that when a number of spherical surfaces are centred on an optic axis and separated by various media, the system can be represented by two ideal surfaces, each of which has its own principal point and nodal point.

In order to construct such a system it is necessary to know:

1. The refractive indices of the media.
2. The radii of the spherical surfaces.
3. The distance of the surfaces from each other.

The cardinal points of the eye can be ascertained from these data.

Position of the Cardinal Points.

The cardinal points of this schematic eye are the position of the principal foci, both nodal points, and the two principal focal points.

Listing accepted the following values as true :

1. The refractive index of air - - -	1
2. The refractive index of the aqueous humour - - - - - -	1·337
3. The refractive index of the lens - -	1·454
4. The refractive index of the vitreous humour - - - - - -	1·337
5. The radius of curvature of the cornea -	8 mm.
6. The radius of curvature of the anterior surface of the lens - - - -	10 mm.
7. The radius of curvature of the posterior surface of the lens - - - -	6 mm.
8. Distance of the front surface of the cornea to the anterior surface of the lens -	4 mm.
9. Thickness of the lens - - - -	4 mm.

He deduced from these data the position of the cardinal points as follows :

1. The first principal focus is 12·8326 mm. in front of the anterior surface of the cornea.
2. The second principal focus is 14·6470 mm. behind the posterior surface of the lens.
3. The first principal point is 2·1746 mm., and the second principal point is 2·5724 mm. behind the anterior surface of the cornea.
4. The first nodal point is ·7580 mm., and the second nodal point is ·3602 mm. in front of the posterior surface of the lens.

Some of the values taken by Listing are at variance with the calculations of other observers.

1. The Refractive Indices of the Media.

These have been variously estimated by different observers. The following are some of the latest :

Substance.	Index of Refraction.	Author.
Cornea - - - - -	1·3771	Matthiessen [1]
Aqueous Humour - -	1·3374	Hirschberg [2]
Capsule of Lens - - -	1·3599	Matthiessen [1]
Outer layer of the Lens -	1·3880	
Middle layer of the Lens -	1·4060	
Nucleus of the Lens -	1·4170	
The Whole Lens - - -	1·4371	Matthiessen [1]
,, ,, - - -	1·4215	Treutler [3]
Vitreous Humour - -	1·3360	Hirschberg [2]

2. The Radii of the Surfaces.

(*a*) *The Cornea.* The radius of the anterior surface of the cornea is about 7·8 mm., which is the mean of numerous measurements. The radius of the posterior surface of the cornea is about 6·2 mm.

(*b*) *The Lens.* The radius of the anterior surface of the lens is about 10 mm. and that of the posterior surface 6 mm.

3. The Thickness of the Refracting Surfaces.

(*a*) *The Thickness of the Cornea.* This is given very differently by different authors. Blix gives it as from ·482 to ·668 mm. and Tscherning finds it 1·15 mm.

(*b*) *The depth of the Anterior Chamber.* This is about 3·6 mm.

[1] *Pflüger's Arch.* vol. xix. p. 543, 1879, and vol. xxxvi., 1885.

[2] *Zentralbl. f. d. mediz. Wissensch.* 1874.

[3] *Klin. Monatsbl. f. Augenheilk.* 1902

(*c*) *The Thickness of the Lens.* This is about 3·6 mm. Nagel[1] taking the following data estimates the cardinal points of the schematic eye as below: The refractive indices, air = 1, aqueous humour = 1·337, the lens = 1·437, and the vitreous humour = 1·337; the radii, anterior surface of the cornea = 7·8 mm., anterior surface of the lens = 10 mm., posterior surface of the lens = 6 mm.; the thickness of the media; anterior chamber = 3·6 mm., lens = 3·6 mm.

The first principal point lies 1·75 mm. behind the anterior surface of the cornea, the second principal point 2·09 mm. behind the anterior surface of the cornea or 5·11 mm. in front of the posterior surface of the lens.

The first principal focus is 13·75 mm. in front of the cornea, the second principal focus lies 22·79 mm. behind the anterior surface of the cornea. The first nodal point is 6·95 mm. and the second 7·29 mm. behind the anterior surface of the cornea.

Both principal points of the eye lie so close together that we can for all practical purposes substitute a point midway between the two in place of both: the same applies to both nodal points.

When the complicated system of the eye is thus reduced to one spherical surface and two media we have the reduced eye, and from it we can calculate the size and position of images formed upon the retina. This simple system consists of a spherical surface with a radius of 5 mm. between a medium with a refractive

[1] *Physiol. des Menschen*, 1905, vol. iii. p. 46.

index of 1 in front and one of a refractive index of 1·33 behind. The nodal points of this simple system lie as in the actual eye near the posterior surface of the lens. The first focal distance of this system is 15 mm., the second 20 mm.

Formation of the Retinal Image.

An inverted image of an object is formed upon the retina by the optical system which has just been described. This inverted image may be seen at the back of an excised eye of an Albino rabbit through the semi-transparent coats of the eye-ball. The size of the retinal image may be calculated, provided that we know the size of the object and its distance from the cornea.

CHAPTER IV.

THE ACCOMMODATION OF THE EYE.

We are not able to see distinctly at the same time objects which are situated at different distances from the eye. The accommodation of the eye is a term applied to the power of the eye which enables it to see objects distinctly at various distances. When the eye is at rest and emmetropic, rays coming from an infinite distance, that is parallel rays, are focussed upon the retina. When the eye is accommodated for a near object and the rays falling upon it are diverging, the anterior surface of the lens becomes more convex and brings the rays to a focus more in front of the retina than when the lens is in a passive condition.

The Mechanism of Accommodation.

Though all are agreed that the anterior surface of the lens becomes more convex during accommodation, there are numerous theories as to how this is brought about. Helmholtz's theory of the mechanism of accommodation is that which is most widely accepted, and is as follows. In a condition of rest, that is during negative accommodation, the lens is kept in a somewhat flattened condition

by the tension of the Zonule of Zinn. In positive accommodation, that is when the eye is focussed for near objects, the ciliary muscle (longitudinal fibres) contracts, pulls forward the choroid and relaxes the Zonule of Zinn, and the lens on account of its elasticity becomes more convex on its anterior surface on account of the relaxation of the Zonule of Zinn, which keeps it flattened. The posterior surface is supported by the vitreous humour, and therefore the anterior surface protrudes forward.

Thomson Henderson's[1] theory of accommodation is based on two facts:

(1) The ciliary muscle is composed of non-striped fibres.

Non-striped fibres do not contract into activity but into a phase of rest, *i.e.*, stomach, bladder, etc.

(2) The zonular fibres in their course from the lens to the ora serrata present a curvature.

A curvature in a non-rigid structure like the zonule cannot exist unless supported.

He maintains that whilst the changes in the lens curvature in accommodation are brought about by slackening of the zonule, yet these results are not produced by contraction of the ciliary muscle but by its relaxation.

The longitudinal fibres of the ciliary muscle are inserted opposite the point of greatest curvature of the

[1] *Ophthalmoscope*, Sept. 1912.

zonule, and therefore when contracted into their phase of rest keep the zonule taut by maintaining and supporting the curvature, *i.e.*, when the eye is at rest as during sleep.

The circular fibres act as a sphincter ciliaris.

In accommodation an associated action of contraction of the circular fibres with relaxation of the longitudinal lowers the zonular curvature and so reduces the tension on the lens. In negative accommodation the opposite takes place, the longitudinal fibres, contracting into a phase of rest, pull upon and increase the zonular curvature, and the circular fibres relax.

The fact that the circular fibres of the ciliary muscle are strongly developed in hypermetropic eyes and either absent or very ill-developed in myopic eyes is in favour of Henderson's view.

Most of the other theories of accommodation have been disproved by observation and experiment.

Proof that the Anterior Surface of the Lens alters its Curvature during Accommodation.

Purkinje-Sanson's Images.

If light be allowed to fall upon the eye through two triangular apertures placed one above each other in a piece of cardboard three pairs of images will be seen. During negative accommodation three pairs of images will be seen. The first pair, which is the brightest of the three, is formed by the anterior surface of the cornea, which acts as a convex mirror. This pair is of medium

size. The second pair, which is of medium brightness, is the largest, and is formed by the anterior surface of the lens. The third pair, which is of medium size and brightness, is inverted and formed by the anterior surface of the posterior portion of the capsule of the lens, which acts as a concave mirror. There are therefore two pairs of erect images formed by the cornea and anterior surface of the lens respectively and one pair of inverted images formed by the capsule of the lens acting as a concave mirror. If the person on whom the observation is being made be now told to accommodate for a near object it will be noticed that though no change takes place in the images formed by the cornea and very little in those formed by the capsule of the lens, the pair formed by the anterior surface of the lens becomes smaller and approach each other as well as approaching the pair of images formed by the cornea. This proves that the anterior surface of the lens has become more convex, as the size of an image formed by a convex mirror depends upon the radius of curvature of the mirror, being largest when the radius of curvature is largest.

The Effect of the Accommodation upon the Cardinal Points of the Schematic Eye.

The following data being taken; refractive indices of the aqueous and vitreous humours 1·3365, refractive index of lens 1·4371, radius of anterior surface of cornea 7·829, radius of anterior surface of lens in negative

accommodation 10, in positive accommodation 6, radius of the posterior surface of the lens in negative accommodation 6, and in positive accommodation 5·5. Helmholtz[1] estimates the cardinal points in millimetres as follows :

			Accommodation.	
			Negative.	Positive.
Focal distance of lens - - -			50·617	39·073
Position of the		First Principal Point	1·753	1·858
,,	,,	Second ,,	2·106	2·257
,,	,,	First Nodal Point	6·968	6·566
,,	,,	Second ,,	7·321	6·965
,,	,,	First Principal Focus	13·745	12·132
,,	,,	Second ,,	22·819	20·955

The last six distances are given for positions behind the anterior surface of the cornea, except the first principal focus, which is situated the distance given in front of the cornea.

[1] *Physiol. Optik*, p. 140.

CHAPTER V.

THE PHYSIOLOGY OF THE IRIS.

The iris has two special functions :

1. It acts like a stop in any piece of optical apparatus, thereby diminishing spherical aberration.

2. It increases or diminishes the amount of light which enters the eye. When it is contracted the cone of light which has its base at the iris is smaller than when it is dilated.

The iris is provided with two muscles, a sphincter and dilator pupillae.

Nerves of Iris.

The constrictor fibres of the iris are supplied by the third nerve, and pass through the lenticular ganglion and to the eye through the short ciliary nerves. The dilator fibres are supplied by the sympathetic root of the lenticular ganglion and by the ophthalmic branch of the fifth, the latter reach the eye through the long ciliary nerves.

The contraction of the pupil through the influence of light is a reflex act, the optic nerve being the afferent nerve and the third nerve being the efferent and the centre being in the brain, the exact positions not having

been finally determined. After division of the optic nerve no contraction takes place when light falls upon the eye, and the same is true when the third nerve is divided.

When light falls upon the eye both pupils usually contract to the same extent. This is called the consensual reflex. When the contraction due to light is removed dilatation takes place through the sympathetic, the constrictor influence being removed.

The Argyll-Robertson Pupil.

In this condition the pupil contracts to accommodation and not to light. It is a common symptom of locomotor ataxia.

Movements of Iris.

1. The pupil dilates :
   (*a*) On removal of light from the eye.
   (*b*) Accommodation for distant objects.
   (*c*) When the aqueous humour is in excess.
   (*d*) In certain emotions, as, for instance, fear.
   (*e*) In dyspnoea.
   (*f*) Upon violent exercise.
   (*g*) On stimulation of certain sensory nerves, as, for instance, those of the sexual organs.
   (*h*) On poisoning by various drugs and in certain diseases.
   (*i*) Through the local action of certain drugs, as, for instance, atropin and euphthalmin.

2. The pupil contracts :

(*a*) When light falls on the eye. Schirmer states that no difference in contraction is found from 100 to 1000 meter candles.

(*b*) When the eye is accommodated for near objects.

(*c*) When the eyes converge.

(*d*) When the aqueous humour is deficient.

(*e*) In poisoning by various drugs and in certain diseases.

(*f*) Through the local effect of certain drugs, as, for instance, physostigmin and muscarin.

CHAPTER VI.

DEFECTS OF THE EYE AS AN OPTICAL INSTRUMENT.

In order that an object in the field of vision may be clearly seen, it is necessary that all the rays of light coming from a point of the object should, after passing through the refracting media of the eye, be brought together at another point at the external surface of the retina. Every deviation from this will cause corresponding defects in the image which is formed. It is upon the fulfilment of this condition that the perfection of definition of any optical instrument depends.

When the light from a luminous point strikes the eye it forms a cone, of which the base is situated on the cornea and the apex at the luminous point. These rays will be refracted by the cornea and the light will enter the eye through the iris. As only the light which passes through the aperture in the iris can affect the retina, a new cone will be formed with its base at the pupil. After refraction by the lens this cone will be brought to a focus. If this focus correspond with the external surface of the retina the luminous point will be seen as a

single point, because at the focus it will be again only a single point. It is obvious that if the focus be formed either in front or behind the retina instead of a point there will be a small circle on the retina. This is called a circle of diffusion. We can with the aid of a convex lens easily observe the phenomena of circles of diffusion. Prick a pin-hole in a piece of black cardboard and place a light behind the cardboard. We can with the lens focus the light coming from the pin-hole on a piece of white paper. It will be noticed that only in one position will there be a clear image of the pin-hole on the paper. If the lens be moved too far away from the paper or placed too close to it, the point will be replaced by a small circle of light, which varies in its size according to the extent which the lens is distant from its correct focussing position.

It follows from this that we are not able to see clearly at the same time objects which are situated at different distances from the eye in the field of vision. In order to convince himself of this fact, the reader should look through a veil at a book situated at a distance of two or three feet; he will find that he is unable to see the meshes of the veil and the printing on the book at the same time. When the image is formed in front of the retina instead of on it through the axis of the eye being too long the condition is called myopia. When the image is formed behind the eye through its axis being too short the condition is called hypermetropia. Emmetropia is applied to the condition when parallel rays

coming from a distance are brought to a focus on the retina without an effort of accommodation.

The power of accommodation gradually diminishes as age advances on account of the lens becoming less elastic. At the age of ten with an emmetropic eye objects can be clearly seen at a distance of 7 cm. from the eye. After this the nearest point of distinct vision recedes further and further from the eye until at the age of seventy-five all accommodation is lost. When the near point has receded further than 22 cm. from the eye the condition is called presbyopia, and spectacles with convex lenses are required to bring back the near point to 22 cm. There are very many variations from the figures which I have given above ; the accommodation may fail much earlier or persist much later. I had a patient who was sixty-three when she consulted me, because she was apparently becoming short-sighted and could not recognise her friends across a street without making a special effort. She did not complain of headache, difficulty in reading or any symptom referable to the eyes and had never had any trouble with her eyes. On examination I found there was hypermetropia to the extent of two dioptres—that is to say, a lens of two dioptres placed in front of the eye would bring the image of an object at a distance to a focus on the retina. The power of accommodation was therefore required in order to see any object distinctly, and therefore the apparent short-sightedness had occurred through temporary relaxation of the accommodation. This case is an example,

of which there are so many, of the existence of a defect accompanied by a compensating superiority which remedies the defect.

There is another defect which is very common, that is astigmatism. If we have a curved surface which is equally curved all round, light coming from a point will be brought to a focus at a point, but if one meridian have a different curvature to the other their focal distances will be different and the rays will no longer be focussed at one point. The bowl of a spoon is an example of an astigmatic surface.

We are, however, chiefly concerned with the defects of an emmetropic eye. I say emmetropic instead of normal, because an eye may have normal refraction and still possess many defects.

In any optical instrument there are two things which have to be avoided as much as possible. They are chromatic aberration and spherical aberration. Both these defects exist to a considerable extent in the eye. It is curious that Euler objected to Newton's conclusion that achromatism in lenses was impossible because, as he said erroneously, the eye was achromatic. It is very easy to demonstrate that the eye is not achromatic. If we look at a spectrum in a spectroscope we find that it is impossible to have the red and the violet in focus at the same time, we are apparently short-sighted, for the violet in comparison to the red, and we shall have to push the eyepiece of the spectroscope further in when viewing the violet. As a matter of fact, a normal

sighted person is short-sighted in violet light. If certain test types which can be read easily at twenty feet but at no further distance be illuminated with blue-violet light it will be found that it is no longer possible to read them. This blue-violet light can be obtained most easily by screening a light with a blue glass in combination with a blue-green glass, which cuts off the red rays transmitted by the blue glass. It is also easy to notice the same condition on viewing a spectrum projected on a screen from a sufficient distance. When the red end is clearly visible as a rectangle the violet end appears blurred and irregular. Most persons must have noticed that a purple light rarely appears as a uniform colour, but either as a red light surrounded by a halo of violet or a violet light surrounded by a halo of red. A purple glass is particularly useful in order to demonstrate these phenomena, nearly the whole of the middle of the spectrum is absorbed whilst the red and violet at the extremes of the spectrum are allowed to pass. If we take the screen with a pin-hole in it and having placed the purple glass behind and also a source of light, we shall see that the pin-hole will either appear as a red dot surrounded by a halo of violet or a violet dot surrounded by a halo of red according as we accommodate for the red or the violet. There is only one position in which the pin-hole can be seen as purple, and that is when the eye is accommodated for a point midway between the red and the violet. In these circumstances the pin-hole appears larger and not so

well defined. All these phenomena can be explained on the view that violet light is brought to a focus sooner than red light—that is to say, when the image for red is formed on the retina the image for violet is formed in front of it. We can demonstrate this with our purple illuminated pin-hole and a non-achromatic lens. It will be noticed that when we focus the rays coming from the pin-hole on a white screen that the screen has to be brought nearer the pin-hole in order to obtain the violet image than the red.

Chromatic aberration has to be taken into consideration when dealing with all problems of colour. I have made mosaics of small pieces of coloured cardboard, using two colours only in each mosaic, the change in colour of the pieces forming the mosaic is very noticeable. It is necessary, therefore, when observing the phenomena of simultaneous contrast to make use of pure spectral colours only.

The emmetropic eye appears to focus chiefly for the central or green rays. This may be demonstrated in the following way. If two sentences be painted on a black ground, the letters being formed by red and blue spots intermingled, one sentence being in red spots and the other in blue, an emmetrope will declare on looking at these from a distance that he sees only a confused mass of red and blue spots.

This shows that the eye of the emmetrope usually focusses for the green rays—namely, those which are intermediate between the red and violet. I have shown

that in this position chromatic aberration is less evident than in any other. If, however, he be rendered slightly myopic by placing a weak convex lens in front of one eye he will at once read the sentence formed by the red dots. If, on the other hand, a weak concave glass be placed in front of his eye so as to make him hypermetropic he will read the sentence formed by the blue dots. In the same way an uncorrected myope will read the red sentence, because the red rays, being less refracted, form the clearest image for him. The hypermetrope will read the blue sentence best because the blue and violet rays being most refracted give him the clearest image. I find that most emmetropes call the purple light of my lantern purple; whilst those who are myopic call it red; those who are hypermetropic call it blue.

Monochromatic Spherical Aberration or Astigmatism.

In addition to chromatic aberration there exists in optical instruments in which lenses form a component part a second form of aberration, spherical aberration. The reason of this is that light of one colour emitted from a point is only brought to a focus approximately by an ordinary lens. There exists, however, certain curved surfaces which are called aplanatic, which reunite in a single point light emitted from a point. The curve for light coming from an infinite distance is an ellipse.

It is obvious that when there is spherical aberration in a system which is situated round an axis the circle

of diffusion which is formed round the image of a luminous point will be a spot of which the greatest intensity will be situated in the axis.

The monochromatic aberrations which are found in the eyes are not symmetrical around an axis, in fact they are asymmetrical and of a kind which should not be found in any well-made optical instrument. It will be seen, therefore, that the term spherical aberration when applied to the eye does not include all cases of monochromatic aberration, as there are other causes than defects in the curvature of the surfaces. The term astigmatism covers all causes.

The irregular astigmatism caused by the lens may be seen by making a pin-hole in a piece of black cardboard. The cardboard should then be held just beyond the far point of the eye, a convex lens being used if necessary to bring the far point near enough to the eye. It will be noticed that there will be either several images of the pin-hole or there will be a star-shaped figure with four to eight rays. This is the cause of the star-shaped appearance of stars and the rays which are seen round street lamps viewed from a distance. Tears and the secretion of the Meibomian glands also cause unequal refraction. When tears are present they form a watery lens which is concave vertically and convex horizontally; this causes the appearance of long rays.

If we now have a luminous object instead of a point the images of diffusion will be formed in the same way, the bright parts combining to form an image. Most

eyes can see two and some many more. For instance, I can in certain circumstances see images which are too numerous to count of an electric light filament. This is the monocular diplopia or polyopia.

After removal of the lens a point no longer appears as a star-shaped figure, though any astigmatism due to varying curvature of the cornea remains.

I find that the best method of observing the figure due to the stellate structure of the lens is to observe a number of lights arranged in a parallel series across a large open surface. The lights on the opposite shore of a lake which is not too large answer admirably for this purpose. When I close one eye and view the street lights in this manner each light has eight rays proceeding from it, forming a star with eight rays. The pattern of each is exactly the same, showing conclusively that the star is not due to a retinal defect but to some cause which can affect the images of all the lights. It will be noticed that when a tear or any foreign matter passes over the cornea the images of all the lights will change in pattern. It will also be found that the images with the left eye have not exactly the same pattern as with the right.

If we observe a concentric series of black and white circles each about one millimetre in breadth at an equal distance apart at a distance well within the power of accommodation, we shall see certain rays which appear light and defined. If we examine these rays we shall see that the lines forming the black and white circles

are definite there whilst the adjacent portions are ill-defined and grey. Moving the figure from the eye also moves the position of the radiating lines. If we now accommodate the eye as for a distant object there will appear on the figure eight or ten sectors separated by fine black lines.

I find that in addition to the appearances mentioned when I look at the disc so that the lines are not clearly visible the central area appears brighter, the brightest portion forming an ellipse round a central dark portion.

Diffraction in the Eye.

Diffraction is caused in the eye by the pupil as a whole, by any irregularities in the borders of the pupil and by any irregularities or small objects in the media of the eye in the course of the rays.

The pupil acts like any small circular aperture, and the images of diffraction formed by its edges are circles alternately light and dark diminishing in brilliancy from within outwards.

The images of diffraction formed by irregularities of the edge of the iris are fine rays brightly coloured. We can see these by looking through a very small aperture with irregular edges. It will be noticed that when the object containing the aperture is turned on its axis in a circular direction the fine rays will move round in the same way.

Defective Transparency of Media.

Any defect in the transparency of the media of the eye impairs the image. As may be seen entoptically,

various cells, small portions of membrane, etc., are to be found in most eyes. The media of the eye may also transmit certain rays imperfectly, as, for instance, the blue when the lens is yellower than usual. The blood vessels are also situated in the path of the rays, with the exception of the non-vascular central portion of the retina.

Defective Centering of the Surfaces.

The various refracting surfaces are rarely absolutely correctly centred, but the deviation is usually so slight as not to cause much impairment of the image.

The defects which I have described produce much less effect on the accuracy of vision than would be supposed for the following reasons. Any particular state which is due to internal and not external causes is soon ignored, as, for instance, the blood vessels of the retina, in fact we have to take special means in order to see them. We judge of differences in the appearances of the images as caused by differences in the stimuli produced by external objects. As we tend to ignore phenomena produced by internal causes I find that as a rule older men have much greater difficulty in seeing some new subjective phenomenon than younger ones. If, however, we pay special attention, some subjective phenomenon or defect becomes increasingly evident, until at last it may become very troublesome.

There is another anatomical condition which has to be considered. The sensitive portion of the retina must

not be considered as a uniform surface, but as a series of points which are placed further apart towards the periphery. The feeble parts of the image will not be intense enough to stimulate a cone, and any stimulation which is caused will be neglected. In nearly all dispersion and diffraction images the centre is much more intense than the periphery.

CHAPTER VII.

THE ACTION OF LIGHT ON THE RETINA.

The optic nerve is not directly sensitive to light, hence the existence of the blind spot in the field of vision. This blind spot occupies about 6° in the field of vision in a position corresponding to the optic disc.

The appearance of Purkinje's blood vessel figures shows that the percipient layer of the retina must be behind the layer containing these vessels. H. Muller [1] found by calculating the positions of the shadows from their projection upon a scale that the rod and cone layer was the percipient layer of the retina.

The following objective effects of light upon the retina have been recorded:

1. Bleaching and regeneration of the visual purple.
2. Alterations in the microscopic appearances of the retinal elements after staining.
3. Alterations in the chemical re-action of the retina.
4. Movements of the retinal elements.
   (*a*) Phototropic of the pigment epithelium.
   (*b*) Contraction of the cones under the influence of light.
5. Electrical changes.

[1] *Sitzungsber. u. Verhandel. d. physik.-med. Ges. Würzburg*, 1852 u. 1854.

1. Bleaching and Regeneration of the Visual Purple.

In the outer limbs of the rods a purple substance is found which is sensitive to light. This purple is sensitive to monochromatic as well as to white light. It is bleached most rapidly by the greenish yellow rays, those to the blue side of these coming next, the least active being the red. This visual purple is found exclusively in the rods.

Several observers had noticed that the colour of the rods was red or rose-red, and in 1876 Boll [1] made the important discovery that this colour was bleached by light.

(1) *Colour of the Visual Purple.*

The name visual purple would hardly convey to most persons a correct idea of the colour of visual purple. If the retina of a frog or a rabbit which has been previously kept in the dark be examined it will be seen to be pink or rose colour, which could easily be mistaken for blood. The term pink or rose would much better describe the colour than purple. The visual purple of fishes inclines more to violet than that of mammals. The maximum of the absorption curve for fishes is found at $\lambda 540\mu\mu$, that for mammals at $\lambda 500\mu\mu$.

Kühne stated that the visual purple in the first change of bleaching became yellow. I have never been able to see this yellow, the colour has always bleached without changing in hue. This yellow colour must have been

[1] *Ber. d. Akad. Berlin*, 1876.

due to the admixture of blood, as when the whole retina is allowed to bleach it becomes more of an orange colour, but if a portion of the external segments of the rods be separated on a glass plate and allowed to bleach, it will be noticed that there is no qualitative change in the colour. Abelsdorff and E. Kottgen [1] find that with apes, rabbits and frogs the purple bleached without changing to yellow. Throughout the bleaching, the absorption maximum remained in the same place, the absorption and the colour of the solution remaining qualitatively unaltered.

(2) *The Distribution of the Visual Purple.*

The visual purple is found exclusively in the rods. It does not follow from this, however, that it is not to be found in regions of the retina in which there are only cones, because the external segments of the rods are dipped in a fluid, which surrounds both the external segments of the rods and cones. The visual purple can therefore diffuse into this fluid and become distributed to every part of the outer layer of the retina. I [2] have found the visual purple between but not in the cones of the fovea. When the retina was first examined the fovea was the reddest part of the whole retina.

Kühne also found the visual purple in a fluid form in one case, but he did not recognise the significance of the observation. He writes [3]: "In one of these eyes

[1] *Zeitschr. f. Psychol. u. Physiol. d. Sinnesorgane*, 12, S. 161.

[2] *Trans. of the Ophth. Soc.*, 1902, p. 300.

[3] *The Photochemistry of the Retina and on the Visual Purple*, by W. Kühne, translated by M. Foster, 1878, p. 34.

which had been laid open in the dark for an hour, I saw to my great surprise the whole of the retinal mass flooded by a clear purple solution which, when poured upon a plate, exhibited the same behaviour as to light as the mass itself." This refers to a retina of a shark.

(3) *The Bleaching of the Visual Purple.*

The visual purple is bleached by monochromatic as well as by white light. Kühne found that the visual purple was bleached most rapidly by yellow-green rays then by green, blue, green-yellow, yellow, violet, orange, red, in the order mentioned. With red light the bleaching is very slow.

(4) *The Regeneration of the Visual Purple.*

The visual purple is regenerated by the pigment cells of the retina, and this will take place in an eye which has been removed from the body, the bleached retina being again laid on the pigment cells. Victor Bauer[1] finds that not only is the visual purple decomposed and regenerated in daylight but that light is plainly a stimulus for its regeneration. In fact, he finds with a suitable light that an intensity can be found by which the regeneration of the purple colour in an eye which is exposed to light is clearly more rapid than in an eye which is kept in the dark. The experiments were made with frogs and white rabbits. Two similar animals were taken and their visual purple bleached by exposure to

[1] *Pflüger's Archiv.*, 1911, S. 490.

direct sunlight, one was then placed in a dark room and the other left with its eyes exposed to light of moderate intensity, either daylight or the light from a glow-lamp. When the retinae of both were examined and compared, it was found that the purple colour was more definite in the eye which had been kept in the light.

(5) *Chemical Characters of the Visual Purple.*

It is soluble in a solution of the bile salts. The purple fluid thus obtained re-acts to light in the same way as normal visual purple.

(6) *Optograms.*

Kühne found that he could take photographs with a rabbit's eye by means of the visual purple. A window with its bars was focussed on a rabbit's retina. This was left from two to seven minutes. Then on examination the parts of the retina corresponding to the light parts of the window were bleached, whilst that corresponding to the bars of the window and frame was only slightly affected. This image was then fixed by drying, which greatly retards the bleaching of the visual purple.

(7) *Fluorescence of the Decomposition Products of the Visual Purple.*

The rod and cone layer of the retina fluoresces strongly in ultra-violet light. The purple itself is not the cause of this fluorescence, because the bleached retina fluoresces more strongly than the unbleached. It is not the

substance of the rods which fluoresces, but the decomposition products of the visual purple.

2. Alterations in the Microscopic Appearances of the Retinal Elements after Staining.

The appearances after staining have been found to be different with a light and dark adapted eye. For instance, the cones have been found with the same stain to be green in the light adapted eye and yellow in the dark adapted eye.

3. Alterations in the Chemical Reaction of the Retina.

The ordinary reaction of the retina is alkaline; this is changed to acid by the action of light.

4. Movements of the Retinal Elements.

(*a*) *Phototropic of the Pigment Epithelium.*

When an eye has been exposed to light, processes of the pigment epithelium are thrown out between the rods and cones until in the maximal position they are restrained by the external limiting membrane. This maximal position is reached after five or ten minutes exposure to bright sunlight. When the eye has been kept in the dark the processes of the pigment cells are retracted into the body of the cell; this dark position of the pigment cells is only reached after the eye has been kept for two hours in total darkness. The most refrangible portion of the spectrum causes a much more marked forward movement than the less refrangible

portion; red light in particular is very weak in this respect.

(*b*) *Contraction of the Cones under the Influence of Light.*

Van Genderen Stort[1] found in the light-adapted eye of the frog that the cones were situated close to the external limiting membrane, whilst in the dark-adapted eye the cones were extended and were found to be quite close to the pigment cells. Engelmann[2] found that the movement of the cones, like that of the pigment cells, is dependent on the nervous system.

5. Electrical Changes.

(*a*) *Current of Rest.*

An eye connected with a galvanometer by means of non-polarisable electrodes shows a positive current, that is a current passing in a direction from the fundus of the eye to the cornea. Waller[3] regards this so called current of rest as a current due to the mechanical injury of the eye.

(*b*) *Current of Action.*

When light falls upon the eye, there is usually a short latent period amounting to 0·2 of a second, then an increase in the positive current, the amount depending on the degree of illumination. A small negative variation at the commencement is often found. Waller and

[1] *Onderzoek. Physiol. Lab. Utrecht* (3), 9, 145.

[2] *Arch. f. d. ges. Physiol.*, 35, (1885).

[3] *Quart. Journ. of Exp. Physiol.*, 1909, p. 170

Gotch find that light of all wave-lengths causes effects of a similar character, dependent upon the degree of illumination, that is to say, all produce like white light an increase in the positive direction. When the light is shut off there is a still further increase in the positive current, that is to say, the effect of darkness after light is very similar to the effect of light after darkness.

Gotch[1] finds that:

(1) Green light evokes a response characterised by a comparatively short latency, and that this reaches the highest maximum.

(2) Red light evokes a response of the same sign, but characterised by much longer latency, and that whilst it also reaches a high maximum, it falls a little short of the green effect.

(3) Violet light evokes a response of the same sign characterised by a latency shorter than that caused by red but longer than that caused by green, and especially characterised by its smaller amount.

Einthoven and Jolly[2] find the latency in the photo-electric reaction of the frog's eye is in complete agreement with the latency of light perception in the human eye.

The period of latency is much longer with weak than intense light.

The effects of light on the retina are easily explained in accordance with the theory that the visual purple is

[1] *Journal of Physiol.*, vol. xxi. no. 1, p. 26, March 29th, 1904.

[2] *Quarterly Journal of Experimental Physiology*, 1908, p. 409.

the visual substance. The contraction of the cones and the movement of the processes of the pigment cells prevent as far as possible the decomposition of the visual purple in the liquid surrounding the cones. In darkness it is necessary to have as large an area of stimulation for the cones as possible, and also to promote as far as possible the free distribution of the visual purple.

CHAPTER VIII.

THE ORIGIN OF VISUAL IMPULSES.

Very little is known at present of the exact nature of visual impulses and of their origin.

The position where visual impulses first arise has been found through calculations based upon the Purkinje blood vessel shadows being projected upon a graduate scale in varying positions of the light. This has been ascertained to be the external third of the retina, that is to say in the layer of rods and cones.

On my theory of vision it will be seen that we have a thin layer of photo-chemically sensitive fluid corresponding to the sensitive plate of the camera. The visual purple is in every respect suitable for the visual substance, and would have been accepted as such, had not Kühne ascertained that it was not present in the cones. As only cones are present in the fovea, the region of most distinct vision, it was not considered essential to vision. This difficulty is entirely obviated by the theory of the relative functions of the rods and cones which has been propounded. Many physiologists have tried to assign different functions to the rods and cones, but all these theories have failed

because all the functions which were said to be the exclusive property of the rods have been found only gradually diminished in the fovea. For instance, Von Tschermak, Hering, Hess, Garten, and I have found the Purkinje phenomenon, the variation in optical white equations by a state of light and dark adaption, the colourless interval for spectral lights of increasing intensity, the varying phases of the after image, in the fovea, only gradually diminished. The complete absence of any qualitative change between the foveal and extra foveal regions is a very important fact in support of the hypothesis that the visual purple is the visual substance. There may be other photo-chemical substances in the retina, but there is not the slightest evidence that such is the case. We could, of course, split the visual purple into innumerable simpler photo-chemical substances, each of which had its own absorption curve, having its maximum in some particular part of the spectrum.

It is difficult to say at present exactly how the visual purple acts as a stimulus transformer, but this is because so many plausible hypotheses immediately occur to us. It is very probable that light acting upon the visual purple is according to its wave length absorbed by particular molecules, the amplitude of their vibrations being increased. These vibrations may cause corresponding vibrations in certain discs of the outer segments of the cones, which seem especially constructed to take up vibrations. We know that when light falls on the retina it causes an electric current. We know how the

telephone is able through electricity to convey waves of sound, and something similar may be present in the eye, the apparatus being especially constructed for vibrations of small wave length. The current of electricity set up by light may cause the sensation of light and the vibrations of the atoms or molecules the sensation of colour. The theory of Nernst as to the origin of nervous impulses may be applied to visual impulses. He holds that nerve impulses are caused by the accumulation of ions against a membrane. The decomposition of visual purple may set free ions which, impinging upon a membrane covering some portion of the cones may set up a visual impulse.

In all vital processes there is a condition of katabolism or chemical change in the protoplasm and an anabolic or building up process in which the protoplasm is restored to its normal state. We have therefore to consider two definite processes in the visual purple—namely, a breaking down of the visual purple photo-chemically by light and its restoration by the pigment cells and rods. Under ordinary conditions of light and during the whole of the day time, the visual purple is continually being bleached and reformed. It is obvious, therefore, that when the eye has been kept in the dark and is then exposed to light an observation taken immediately will not be comparable with one taken a few seconds afterwards, because in the first observation we have only to consider the katabolic change, whilst in the second observation the anabolic change has to be

considered as well, as the visual purple has to be reformed for subsequent seeing. There appears to be very little evidence in ordinary circumstances of this anabolic process. The retina, therefore, corresponds to a layer of photo-chemical liquid in which there are innumerable wires, each connected with a galvanometer. When light falls upon a portion of this fluid the needle of the galvanometer corresponding to the nearest wire is deflected. The wires correspond to the separate fibres of the optic nerve, and the galvanometers to the visual centres of the brain.

It may be well here to deal with the objections which have been raised to the visual purple being the visual substance. The chief objection—namely, that it is not present in the fovea—has already been disposed of by finding that although it is not present in the cones it is present around them. The other objections have on examination very little weight, and are mostly based on erroneous statements. They are that animals such as frogs, naturally possessing the pigment, continue to see when their visual purple has been absolutely bleached, as it may be by prolonged exposure to strong light, and that the visual purple is entirely wanting in some animals which see very well. On the first point it may be well to quote Kühne. He writes: "Without direct sunlight I have never succeeded in a room in obtaining frogs' retinae free from visual purple, not even when I allowed the animals to leap about before the window the whole day long." My contention is that in those

cases in which the retinae were bleached by sunlight and the frogs were still able to see, there was sufficient visual purple or its decomposition products for vision, but not enough for external recognition. The experimental conditions are in these cases so difficult as to make it quite impossible for anyone to say that no visual purple was present. I have again and again examined the retinae of animals which contained visual purple, as, for instance, monkeys, and in many cases failed to detect any even when the animal has been kept in the dark for a considerable period before the retina has been examined. The same applies to the second objection, and where animals have been stated to have no visual purple or no rods, subsequent observers have found both. It was stated formerly that the invertebratae do not possess visual purple, but it has been shown that in the eye of the butterfly there is a photo-chemical substance which is rapidly bleached and reformed. The bat was formerly stated not to possess visual purple, but Trendelenburg has written two papers on the Sehpurpur auf die Fliedermaus. It was formerly stated that a tortoise possesses only cones, but on examining the retina of a tortoise I found the rods and cones as definitely marked and distinct from each other as in man. Even if there were no visual purple the argument fails, because there might be some other means of stimulating the cones. It is again interesting to quote Kühne on this point: "According to all appearance the visual purple in a bird's eye is deficient in proportion as the

retina is provided with other more stable means of absorbing coloured light, I mean the coloured globules of the cones. This is at least the case in the nocturnal and predaceous birds, and is entirely true as regards the pigeon and the fowl."

It would seem likely that the photo-chemical processes necessary for vision must have an elaborate nervous mechanism which could only arise from the retina. The peculiar arrangements of the rods seem to indicate that these are the elements involved. Kühne writes: "It must not be forgotten that the retinal epithelium of the choroid has been proved to be a very important physiological or chemical constituent of the retina, or, stated shortly, as a purpurogenous gland, the cells of which can scarcely fail to possess a very peculiar complicated innervation. Now I do not see that irritable fibres can arise from other source than from the nervous mass of the retina." It does not appear to have occurred to Kühne that the rods were the nervous elements for which he was seeking. He looked for some direct connection between the rods and the pigment cells. We know that in other parts of the nervous system it is sufficient to have contact between two cells without direct continuity.

CHAPTER IX.

LIGHT AND DARK ADAPTATION.

The importance of the change which takes place when a person goes from the light into a dark room has only in the last few years been recognised. During the day and in a bright light the eyes are in a state of light adaptation, that is to say they are adjusted so as to be able to see in a bright light. When the light is feeble a different state of the eyes is required, and this state is called that of dark adaptation. Most are aware of the difficulty of seeing when we go from a brightly to a dimly lighted room. A certain amount of time is required before we can see objects in the room, but on remaining in the room the eyes become more and more sensitive to light until we are able to see quite clearly objects which were invisible when we first entered the room. This increase of sensibility by the state of dark adaptation has been shown by Piper[1] to vary very considerably with different persons.

Various observers have noticed an increased sensibility of the eye through the exclusion of light for

[1] *Zeitschr. f. Psychol. d. Sinnesorg.* 31, S. 161.

mechanical and electrical stimuli and for ultra violet, Röntgen and Becquerel rays.

On the theory of vision which I have given many explanations of dark adaptation are possible, all of which are consistent with the facts. The accumulation of the visual purple in the liquid surrounding the cones may be sufficient, the liquid becoming more and more sensitive to light as the percentage of visual purple in it increases, or some additional substance may be added to the fluid making it more sensitive to light. This may be caused by the withdrawal of light from the eye or by hormones formed because of the reduction of light on other parts of the body. Again the withdrawal of light may cause a mechanical arrangement which is specially favourable to photo-chemical decomposition by a weak light. Perhaps all these causes are in operation. We know that when the eye is in the dark the processes of the pigment cells with their pigment are retracted and the cones are also pushed further away from the external limiting membrane. This would increase the size of the space and also the area of the surface of stimulation of the cones. In the case of a light adapted eye the opposite is the case, the processes of the pigment cells with their pigment being pushed forward and the cones being retracted against the external limiting membrane. This would have the effect of isolating impressions and preventing the free flow of the visual purple, thus requiring a greater stimulus. We know that light acts as a stimulus to

the regeneration of the visual purple, and therefore though more is used up more is formed. When we go from a dark to a light room, the dazzle and excessive sensation of light are just what we should expect through an accumulation of photo-chemical substance.

CHAPTER X.

VISUAL ACUITY.

If two small points of light fall upon the eye, unless these are a certain distance apart they will appear as a single point of light. The region of the fovea is that at which two points can be distinguished with greater ease than any other part of the retina. The limit of visual acuity is usually given as 50″, though with strong contrast some observers have been able to distinguish two points when even closer together than that. Two points which are easily distinguished as distinct when seen centrally rapidly become one when viewed with the peripheral part of the retina. Dor gives the diminution of the visual acuity from the fovea to the periphery of the retina as follows: The centre of the fovea being counted as 1, at

5°	outwards	the	visual	acuity is	$\frac{1}{4}$
10°	,,	,,	,,	,,	$\frac{1}{15}$
15°	,,	,,	,,	,,	$\frac{1}{30}$
20°	,,	,,	,,	,,	$\frac{1}{40}$
25°	,,	,,	,,	,,	$\frac{1}{50}$
30°	,,	,,	,,	,,	$\frac{1}{70}$
35°	,,	,,	,,	,,	$\frac{1}{100}$
40°	,,	,,	,,	,,	$\frac{1}{200}$.

The Influence of Stimulation of the Periphery of the Retina upon Vision with the Centre.

(1) If we look at two small isolated stars of equal magnitude either may be made to disappear by looking fixedly at it, whilst the other remains conspicuously visible. The phenomenon is most marked on a dark night, and when the star looked at is in a portion of the sky comparatively free from other stars, and when only one eye is used. On a very dark night a considerable number of small stars, occupying the centre of the field of vision, may be made to disappear, whilst stars occupying other areas of the field of vision are plainly visible.

(2) Other lights or objects, when small and with dark surroundings, as, for instance, a piece of white cardboard on black velvet, may be made to disappear in a similar manner.

(3) No change can be observed if a very bright light, a group of stars, or a uniformly illuminated surface be made the subject of the experiment.

(4) If in a dimly lighted room a piece of black velvet about 3 feet square be fastened upon a door and in the centre of the velvet a pin be inserted so that the head faces the observer, the head of the pin is a conspicuous object surrounded by the black velvet. If it be looked at fixedly with one eye it will disappear, and after a few seconds the whole of the black velvet and door will disappear, and the visual field becomes considerably contracted, the wall-paper on either side of the door appearing to unite.

(5) The darker the surroundings, the brighter will be the light which is made to disappear. When these experiments are made with a lantern, the result is very startling. One moment we are looking at a bright light, and the next have the sensation of having become quite blind, the sensation of absolute blackness being greater than can be obtained in any other way. Just before the light disappears, it appears to pulsate, appearing and disappearing as if a rose diaphragm were shut and opened before it, except that the re-appearance of the light is always from without inwards. The same appearance may be seen with the stars on a dark night. The chief essentials in making a bright light disappear are to use only one eye, and to have the surroundings of the light absolutely dark. In my experiments which I made at night I used a specially constructed lantern, which I viewed through four open doors, so that all extraneous light could be as far as possible excluded.

(6) If a small light be viewed in a dark room with one eye, the eye will continually move. If, for instance, a white spot be made on dark paper, it will be found that the eye has much less tendency to move when the white spot is surrounded by a number of other white spots, and in these circumstances will also be seen brighter.

The facts of visual acuity may be explained on the theory of vision as follows: The images of a series of parallel white and black lines will fall upon the retina and decompose the photo-chemical liquid there.

Fig. 2 is a drawing which I have made from a microscopical preparation of the external surface of the fovea.

Fig. 2.

It will be seen that the cones are arranged in nearly parallel lines but with a slight curvature inwards. Each cone is separated by a space which is about the diameter of a cone. The images of two parallel black lines are represented on these cones. It will be seen that the cones will be stimulated according to the degree of photo-chemical decomposition of the liquid surrounding them.

M. Schultz gives the diameter of a cone in the fovea as from ·0020 – ·0025 mm., H. Müller ·0015 – ·0020 mm., Welcker ·0031 – ·0036 mm. With Listing's schematic eye a visual angle of sixty seconds corresponds to an image of ·00438 mm. on the retina, though the diffusion circles make the image cover an area ten times as large, but the intensity of the image of a point of light is greatest in the centre of the circle and diminishes towards the circumference. It will be seen that in order that two points of light should be distinguished as two instead of one, at least one cone must intervene between those which are stimulated by the points of light, that is to say, a cone which is not stimulated intervening between two which are stimulated gives rise to a sensation of blackness. It will be seen from Fig. 2 that a series of parallel black and white lines will be seen either as a chess board pattern or if larger as beaded. The fact that this is so was pointed out by Purkinje. The result of light

impinging upon the retina in the space between two cones would result in the stimulation of both these cones equally if the image of the point of light were at an equal distance from both, but one would be stimulated more than another in proportion to the distance from it of the image of the point of light. On the older view—namely, that the cones were directly stimulated by light—there should be evidence of absence of sensation when the light falls upon the intervening spaces between the cones. No evidence of this has been adduced.

CHAPTER XI.

POSITIVE AND NEGATIVE AFTER-IMAGES.

Positive and negative after-images are designated as such in the photographic sense: that is to say, in the positive after-image the light parts correspond to the light parts of the object and the dark parts correspond to the dark portions of the object. In the negative after-image the reverse is the case, and the light parts of the object are seen as dark and the dark parts are seen as light.

A positive after-image is seen very well in the morning; if on awaking the eyes be directed towards a window and then immediately closed and covered with the hand, a positive after-image is seen of the window. If the window be subtended by a white cloud the light parts of the window appear rose-coloured and the bars dark.

If a coloured object be fixated for ten to twenty seconds and then the eyes be directed towards a uniform white surface a negative after-image is seen of approximately complementary colour. In ordinary circumstances a period of short duration and subsequent occlusion of the light favours the development of the positive after-image, whilst a period of long fixation and subsequent stimu-

lation by light favours the development of the negative after-image.

1. Separation of the Positive and Negative After-Images.

Both eyes must be carefully covered with the hands for several minutes whilst the right eye is directed forwards so that when the hand is removed a small triangular piece of white paper on a large sheet of black paper is visible. The small piece of white paper should be illuminated by the sun. On removing the hand and then immediately replacing it so that the piece of paper is visible for the shortest possible period of time, a triangular positive after-image of the paper is seen; this first appears a dazzling white, then becomes violet, which gradually becomes more and more purple, and then fades away without becoming negative, and lasting for a period of from 8 to 12 seconds. On letting light through the lids the image is seen as dark (negative).

If, when the after-image has existed for two seconds and when particular note has been taken that there is no other after-image in the field of vision, a sharp quick jerk be given to the head, down and up, the after-image will apparently move upwards in the field of vision. It will no longer be triangular but appear as an irregular circle with portions detached. If now the fingers be moved very carefully so that a certain amount of light enters the eye through the lids a clear cut triangular image will be seen in the field of vision in the original position of the after-image and below its secondary

position. The image appears as a dark triangular portion on the reddish-yellow field formed by the light through the eyelids. Whilst the positive after-image has moved the negative after-image is found in the original position.

2. Two Negative After-Images from one Light Stimulus.

If the above-mentioned experiment be repeated and the positive after-image be allowed to remain in its secondary position for two seconds before allowing light through the eyelids two negative after-images will then be seen, one triangular in form and very faint corresponding to the primary position of the after-image and one much darker and irregular in shape corresponding to the secondary position of the after-image.

3. Blending of Positive After-Images.

If on awaking, one eye (the other being covered) be directed towards three windows in a line and separated by portions of wall and the eye be immediately closed and covered with the hand and after one or two seconds the head be shaken from side to side, the light parts of the after-image will blend into one uniform rectangle of light, the dark parts disappearing. On allowing light to enter through the eyelids a negative after-image of the windows is seen in the original position occupied by the positive after-image. If, however, the head be immediately shaken after the perception of the positive after-image the negative after-image only appears as

an ill-defined portion corresponding to the blended after-images.

4. Subjective Effects of Distributed Photo-chemical Material.

If a positive after-image be obtained for one eye and the light immediately excluded, on shaking the head the after-image is apparently distributed over the retina. I have then found that four definite subjective appearances may be seen, though it is rare to see more than one of these at the same time.

(*a*) *The Star-figure or Portions of it* (cf. Fig. 10). In this case when the centre is seen the whirling in this portion described on page 90 is very noticeable. When the outer part is seen this forms a wide-meshed network of bright lines.

(*b*) *Cone Figure* (cf. Fig. 7). The appearance corresponds to the outer aspect of the cones of the retina—that is to say, numerous bright points in the centre and rather larger circles separated by wider intervals externally.[1]

(*c*) *Checkered Figure.* The greater part of the visual field may appear as if covered by small squares alternately light and dark like a chess board ; these squares in the centre are very small, not much larger than the points just described, only they appear square instead of circular.

(*d*) *Brush Figure.* A number of short bright lines

[1] When red light is used, the points are all bright red.

all over the visual field may be seen. These lines have a length about six times their diameter. All are pointed forwards like a brush viewed from the bristle side, the lines are not, however, parallel to each other except in different regions of the visual field. They all point forward, but at different angles in different regions.

5. After-Image of Mosaic of Red and Blue Squares on a White Ground.

If a mosaic of pieces of red and blue cardboard of about a centimetre square be pasted on a white ground and then a positive after-image be obtained in the usual way, it will be noticed that the positive red after-image disappears much more quickly than the blue. The colours also disappear more rapidly than the light effects, the mosaic being surrounded by white appears as a positive after-image dark on a white ground long after the colours have disappeared. No detail is seen in the mosaic, only a uniform dark rectangle. In this method the period of light stimulation being as short as possible it is difficult even if bright sunlight be used to obtain a complementary coloured after-image. The after-image of the whole, including the white surround, often becomes purple. This is particularly noticeable when the eye has been covered with the hand for a little longer than usual before making the experiment.

When a spectrum on a screen is made to disappear suddenly it will be noticed that the colours do not all vanish at once. The red disappears before the blue.

This explains the fluttering heart illusion. When a mosaic similar to that mentioned above is moved from side to side in a bright light, preferably sunlight, the blue appears to slide over the red. This is explained by the fact that the blue positive after-image is more persistent than the red. There is another illusion in connection with this mosaic which I have not seen previously mentioned. When the mosaic has been moved from side to side two or three times, the whole of each line formed by the red and blue squares appears as if tilted forwards at an angle of about 30°. It appears as if we were looking at a series of troughs, each formed by a line of blue and red squares, instead of a plane surface.

6. Negative After-Image retains its Shape and does not move.

If a negative after-image of a coloured light, *e.g.* red, be obtained in a dark room the blue-green after-image moves with the eye, but does not change its relative position in the field of vision. On shaking the head it disappears, but on keeping still it reappears by degrees at exactly the same point and is of exactly the same shape as before, it gradually disappears without changing colour.

7. Star Figure in After-Image of Spectral Red.

When a negative after-image of spectral red has been obtained the star figure in red (cf. Fig. 10) is often seen in the centre of the blue-green negative after-image.

8. Certain Phases of the Positive After-Image.

If two rectangular strips of white paper about three inches long and a third of an inch wide be placed on a piece of black velvet and separated by a distance of an inch, definite positive after-images may be obtained of the two strips by viewing them with one eye, the eye being directed to a point midway between the two strips of paper, the other being closed and covered with black velvet, for the shortest possible time the eye being simply opened and closed. Two clear cut positive after-images will first be seen; these rapidly become blurred and gradually approach each other, the central portions of each appearing to bulge towards each other and to combine first; the upper and lower portions disappear first, the two after-images gradually combine in the centre of the field of vision, the last phase being a white circular blur, which slowly disappears with a whirlpool movement. It will be noticed that the after-images do not become negative.

THE NEGATIVE AFTER-IMAGE OF BLACK.

The negative after-image of black is green, not white. This can be seen very easily by regarding intently a black object and then looking at a white one, as at the snow. The best black object is a hole from which no light can be reflected. The fact that the after-image of black is green gives an explanation of a pretty little toy which excited much interest a few years ago,

Benham's top. This consists of a disc divided into two semi-circles, one white and one black : on the white half there are black lines at intervals and at different distances from the centre. When the top is turned so that the black half precedes the white one the black lines nearest the black half appear red. This red is the contrast colour to the green which is seen as the after-image of the black semi-circle. The after-image of black varies with the intensity of the light employed : in a feeble light it is white, raise the illumination it becomes yellow, raise it again it becomes yellow-green, increase it further it becomes pure green, try the experiment in the sunlight and it becomes blue-green.

CHAPTER XII.

THE TIME RELATIONS OF VISUAL SENSATION.

It has not yet been ascertained whether there be a stimulus of sufficiently short duration not producing an effect upon the eye. An electric spark which has a duration of a very small fraction of a second produces a very definite effect upon the eye.

The Effect of a Stimulus of Short Duration.

If a bright object be rapidly moved in an absolutely dark room or if a bright object be shown for a fraction of a second, six definite stages will be seen before the visual field resumes its normal appearance.

(1) The primary image.
(2) A dark interval.
(3) The secondary image.
(4) A second dark interval.
(5) A tertiary image.
(6) A dark phase which lasts until the visual field resumes its normal appearance.

The secondary image has been the subject of much discussion. It was first observed by Purkinje.[1] It appears in an interval of about one-sixth to a quarter of a second after the commencement of the primary

[1] Purkinje, *Physiol. d. Sinne*, vol. ii. p. 110.

image. Von Kries has stated that the secondary image is not to be found at the fovea. But this appears to be due to his method of experimentation, as a retardation of the image would produce exactly the same effect. Hess [1] points out that in the foveal region the secondary image is bent outwards. (See Fig. 3.)

I quite agree with Hess that the secondary image can be seen in the fovea, and this can be demonstrated easily in the following way: If a strip of white paper be moved backwards and forwards over a dark background in a dimly lighted room it will be noticed that after a dark interval the piece of white paper is followed by the secondary image, which becomes bent outwards when the central portion of the field of vision is reached. Hess also finds that the secondary image is seen with red light.

The following method [2] shows still more conclusively how the recurrent image can be seen in the foveal region. A series of small electric lights should be arranged in a straight line in a dimly lighted room and the observer be situated at such a distance that the image of the

[1] *Pflüger's Arch.*, Bd. 95, 1903.

[2] *Journal of Physiology*, vol. xlv. Nos. 1 and 2, page 73.

centre light falls upon the foveal regions of his retinae. On closing one eye and covering that eye with the hand the centre light is carefully observed whilst another person turns out all the lights simultaneously; these are allowed to be visible for about a second. Four definite stages will be noticed, that is to say, 1. Continuation of the sensation. 2. Period of darkness. 3. The recurrent image. 4. Period of darkness (negative after-image), in which the details of the objects, such as the outline of the filament, can be noticed. In the second stage both the light and the dark parts of the object appear dark and no details are observable. It will be seen that the recurrent image is more marked in the foveal region than anywhere else, in fact, it might be missed in any other part. The above phenomenon can be seen very easily with the electric advertising signs which are so common and in which a number of illuminated letters appear and disappear at short intervals.

The fourth stage lasts longer than the third and the fifth much longer still. Hess gives fifteen seconds as the duration of the six stages, the last ten seconds are occupied by the sixth stage.

The curving of the secondary image can be explained by a retardation of the sensation in the foveal region. Hess lays particular stress upon the fact that the phases, especially the three bright and three dark phases, are similar for the region in which there are only cones to that in which rods are found.

The Effects of Intermittent Light.

When light falls upon the eye the primary image occupies a certain definite time. If two stimuli fall upon the eye at an interval so short that the primary effect of the first stimulus has not passed away before the second stimulus impinges upon the retina, the result is a continuous sensation. This is the fact upon which cinematography is based. When the interval between the two stimuli is not sufficiently long flicker is noticed, and the appearance or disappearance of this flicker depends upon certain conditions.

(1) Influence of the intensity of the light.

If an intensity of light which requires flashes to succeed each other at 18·96 per second be taken, then at 4 times this intensity Baader finds that the rate will have to be 24·38 per second, for 18 times 29·84 ; for 193 times 41·31 ; for 1800 times 50·24 per second.

(2) Variation of the surroundings causes a change in the rate at which flicker disappears.[1]

(3) T. C. Porter[2] has shown "that the apparent luminosity of two flickerless discs under the same illumination may be precisely the same, and yet the angle of the black sector may be different in the two discs ; indeed, one disc may be entirely white and the other may have a black sector by no means small under some conditions of illumination, and these

[1] Sherrington : *Journal of Physiology*, 1897, vol. xxi. p. 33.

[2] *Contributions to the study of Flicker, Proceedings of the Royal Society, A*, vol. lxxxvi. p. 502, 1912.

two may, to the eye, form a perfect match when flickerless."

(4) Flicker disappears sooner from the central than the peripheral parts of the retina. Exner[1] and Charpentier[2] also found that the size of the retinal image was a factor in the disappearance of flicker. When the size of the retinal image was increased the point of fusion was raised. Billarminoff[3] found a higher frequency necessary for fusion on the nasal than on the temporal half of the retina with certain kinds of light.

[1] *Sitzungsberichte der K. Akademie der Wissenschaften, Wien,* 1868, Band lviii. Abth. 2, S. 601.

[2] *Archives d'Ophtalmologie,* Paris, 1890, tome x. p. 340.

[3] *Archiv für Ophthalmologie,* 1889, Band xxxv. Abth. 1, S. 25.

CHAPTER XIII.

VARIATIONS IN LIGHT SENSATION.

Purkinje Phenomenon.

Purkinje stated that if a red and blue of equal intensity be diminished in the same proportion, the blue appears much brighter than the red. This is easily noticed as twilight approaches, red flowers become dark or black whilst blue flowers are conspicuously visible. The same change is noticeable in the colours of a stained glass window. If a spectrum be gradually diminished in intensity the point of maximum luminosity gradually shifts from about the region of the D Line to the blue side of the E Line with a spectrum of very diminished intensity. König gives $\lambda 535$ for the weakest light, $\lambda 615$ for the strongest.

Hering[1] finds that the state of adaptation of the eye is the chief factor in the production of the Purkinje phenomenon. He finds that the intensity of an equally bright red and blue may be reduced without altering the relative luminosity. The luminosity of the equally bright red and blue may be left unchanged, and yet the Purkinje phenomenon will appear if the eye be dark

[1] *Arch. f. d. ges. Physiol.* 1895, S. 519.

adapted. He lays particular stress upon the alteration in the saturation of the colours.

The matching of spectral colours with white light will vary in the results according to the state of dark adaptation of the eye.

The Purkinje phenomenon is a photo-chemical phenomenon, and is found with other photo-chemical substances. All know that we can recognise red light at night when the eye is dark adapted, and I find this is the case with the extreme periphery of the field of vision. The Purkinje phenomenon is found for localised areas of the field of vision, that is to say, when the eye is fixated upon a black object this region becomes locally dark adapted and the Purkinje phenomenon is found with it. If we look at a red and a blue object through a pinhole, taking care that the eye does not become dark adapted, if the red object be brighter than the blue in ordinary circumstances it still appears brighter through the pinhole.

In the Centre of the Field of Vision.

A hole of about 2 cms. (in diameter) is made in a door between two dark rooms; the hole is filled with two glasses, one red and one blue, placed one above the other so that half is red and half blue, the red being decidedly in ordinary conditions the brighter of the two; a lamp with an obscured glass moveable on a bench is arranged immediately behind the two glasses. When the lamp is close to the glasses the red is decidedly brighter than the blue in all positions of the eye. When the lamp is

moved a certain distance away from the glasses, it will be noticed that, whilst the red is the brighter of the two when the image falls on the fovea, on moving the eye so that the image falls peripherally the red is seen very dark or black and the blue is seen as a bright white light. On moving the lamp still further away it will be noticed that the blue will be seen the brighter of the two even with the fovea. This experiment reconciles the statements of those who declare that the Purkinje phenomenon is to be found in the fovea with those who declare that it is to be found in the periphery and not in the fovea; results depend on the intensity of the light employed.

Simultaneous Contrast.

There are two kinds of simultaneous contrast, simultaneous luminosity contrast and simultaneous colour contrast.

Simultaneous Luminosity Contrast.

When the same grey is placed upon black and upon white it appears darker upon white than it did upon the black. When a black square is placed upon a white surface and regarded intently without moving the eyes it will be noticed that the black appears to become lighter. A number of fine white particles appear to invade the black surface and make it become lighter and lighter.

Simultaneous Contrast is most marked where the contrasting surfaces touch, and appears to be due to an exaggerated perception of relative difference.

CHAPTER XIV.

VARIOUS VISUAL PHENOMENA.

1. Appearances in the Field of Vision due to Peculiarities of the Yellow Spot.

1. *Loewe's Experiment.* If we look at a clear white surface through a solution of chloride of chromium, which is of a celadon green colour, we shall see a purple spot in the centre which varies in size and shape with different persons. On careful examination it will be found to consist of three portions, the centre corresponding to the fovea appears as a bright purple disc, the middle corresponding to the non-vascular portion of the yellow spot appearing as a dark green ring, and lastly Loewe's ring corresponding more or less accurately to the outer feeble yellow portions of the yellow spot, which appears as a purple ring surrounding the central portion and possessing a diameter twice or three times as large.

2. *Apparent Size of Regions of Yellow Spot in Field of Vision.* The region corresponding to the yellow spot occupies a considerable area in the field of vision. I find that the visual angle which any portion subtends can be easily measured by projecting the after-image of an

object occupying a known visual angle on the sky above a house. A comparison is easily made in both cases with portions of the house. If an observer look straight at the cloudless sky, preferably about three hours before the sun sets, for about ten to twenty seconds, a disc or an ellipse with the long diameter horizontal, and which is to me of about nine degrees, appears in the sky. Inside this is a central darker portion of about two degrees in

Fig. 4.

each diameter, and this surrounds a central brighter portion which corresponds to the point of direct vision. This is about 40 to 50 minutes in diameter and is circular in form. (See Fig. 4.)

Helmholtz[1] gives a disc of the diameter of about 40 to 50 minutes as the apparent size of the fovea in the field of vision and the diameter of the aureola, which corresponds to the non-vascular portion of the yellow spot and is the portion where the yellow is most intense,

[1] *Physiol. Optik*, p. 567.

as about two degrees. This is correct for me. The remaining portion which corresponds more or less exactly to the remainder of the yellow spot is Loewe's ring.

3. *Appearances of Central Region with Different Intensities of Light.* Exner[1] points out that with feeble light the central region is seen as a dark disc surrounded by Loewe's ring, and that as the intensity is increased this region becomes brighter and brighter until it becomes more luminous than its surroundings, the fovea being specially noticeable as a bright disc of greater intensity than any other part.

The appearance of Loewe's ring varies with different persons and in different conditions. Loewe saw the ring circular and so do I, but Helmholtz saw it rhomboidal. I see all three portions circular in the conditions I have just mentioned and every part is darker than the surrounding sky, the region corresponding to the fovea being the brightest of the three. I have seen after looking at the sky the central portion of the yellow spot appear as a bright yellow spot, with a dark centre. It was circular in form, and on one occasion lasted for ten minutes before disappearing.

When the light is feeble the foveal region is not seen and the central dark portion is larger and Loewe's ring is smaller. The shape is then more often oval, rhomboidal or irregular. Fig. 5 shows the appearance to my right eye on a dark night with a cloudless sky. The dark centre was surrounded by a lighter portion. Bright

[1] *Ctrlb. f. d. Med. Wssnsch.* S. 594, 1868.

lines then came from the periphery and proceeded in an irregular manner to the centre. When these lines reached the centre each broke up in a very similar way to a rocket and left the surrounding portion lighter than before. This continued until the yellow spot region became lighter instead of darker than the ground.

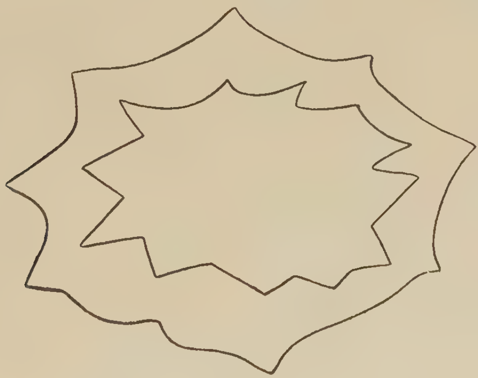


FIG. 5.

I have seen the yellow spot region largest and darkest when on waking in the early morning I have directed my eyes to the white ceiling. The whole of the centre portion of the field of vision appeared as a black disc surrounded by luminous circles. These circles then interlaced and encroached on the central black portion, which disappeared from without inwards.

There are several ways in which the region of the yellow spot may be seen bright on a dark ground. Helmholtz [1] has seen it on waking in the morning and looking at a dark background after having first exposed the

[1] *Optik Physiol.* S. 569.

eyes to the light from a large window. A disc of dazzling brightness is seen of the size of the non-vascular aureola of the yellow spot.

I find that the region corresponding to the non-vascular portion of the yellow spot can be seen very well as a bright spot on a dark ground in the following way: If one eye be closed and the other directed to the sky through a deep red glass, after ten or twenty seconds the central portion will appear purple instead of red.

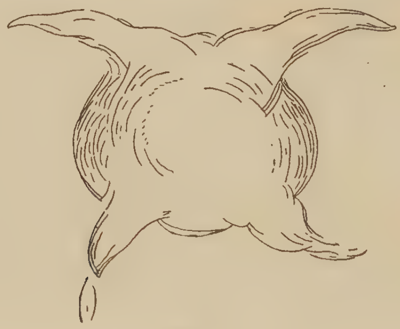


FIG. 6.

If the eye be now closed and covered with the hand so as to exclude all light, the field of vision appears green, with the exception of the centre, which is seen as a bright red spot, much brighter than the rest of the field. The green gradually invades this red from without inwards until the whole field of vision is one uniform green and the centre becomes of similar brightness to the parts surrounding it. (See Fig. 6.)

Fig. 7 shows a sector of one of the subjective appearances of the central region as seen by me on awaking

in the morning. The centre has a spotted appearance, the circles being larger at the periphery, with gradually increasing black intervals. Outside the macular region the spots of light are further apart and less defined.

The retina after a night's rest is in a most favourable state for entoptic experiments. On awaking in the morning and then directing the eyes to a white ceiling the region corresponding to the yellow spot is marked out as an oval black patch and light appears to invade

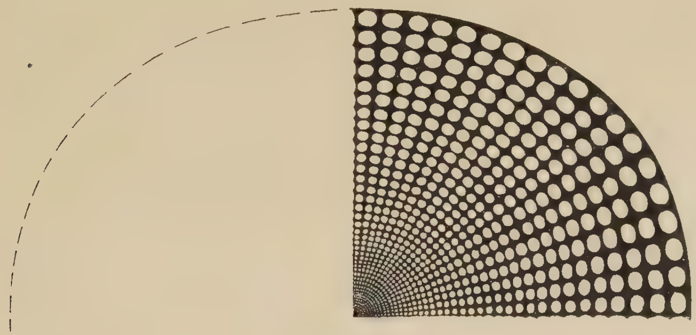


FIG. 7.

this patch from without inwards. Helmholtz concludes from this that light is perceived an instant later in the central as compared to the peripheral portions of the retina. Helmholtz attributes this observance to Maxwell,[1] but as a matter of fact Maxwell said exactly the opposite. He said : " If we look steadily at an object behind a series of bright bars which move in front of it, we shall see a curious bending of the bars as they come up to the place of the yellow spot. The part which

[1] *Report of Brit. Assoc.* ii. p. 12, 1856.

comes over the spot seems to start in advance of the rest of the bar, and this would seem to indicate a greater rapidity of sensation at the yellow spot than in the surrounding retina."

I agree with both of these apparently contradictory statements.

4. *Yellow Spot Region Seen on Opening an Eye.* I find that if one eye be directed to the sky whilst the other eye is closed and covered with the hand, when the second eye is opened the region corresponding to the yellow spot is seen as a much lighter spot. This phenomenon is seen very well at night when there is a clear sky.

5. *Bright Spots Seen in the Field of Vision.* I have several times noticed on stooping on a sunny day that bright spots have appeared in the field of vision. These have formed a circle which gradually contracted, each spot becoming smaller and brighter as the centre was reached. The appearance exactly corresponded to Fig. 7 seen from without inwards.

II. Entoptic Appearances of the Yellow Spot and the Blood Vessels of the Retina.

The yellow spot and the blood vessels of the retina may be seen entoptically in several ways. Purkinje described the first three methods.[1]

1. *Illumination through Sclerotic.* If by means of a lens of short focus a light, as intense as can be endured without discomfort, be concentrated on the sclerotic

[1] *Btr. z. Knntn. d. Sehens*, S. 89, 1819. *Neue Btr.* S. 115, 117, 1825.

as far as possible from the cornea whilst the eye is directed towards a dark surface the vessels of the retina will be plainly visible on a yellowish red background. The finest capillaries can be seen, and it will be noticed that these are absent in the centre of the field of vision, the vacant space being bordered by the loops of the capillaries. Whilst the portion of the field of vision corresponding to the rest of the retina appears of a uniform illumination, that in the centre where there are no capillaries is brighter, and has an appearance similar to that of the fovea under the microscope, in which the cones are seen as a series of small round circles, when the retina is viewed from its external side. (See centre of Fig. 7.) Helmholtz describes the entoptic appearance of this central non-vascular portion as being similar to that of shagreened leather. If the light be moved upwards on the sclerotic whilst the eye is kept fixed the images of the vessels appear to move in the same direction whilst the central non-vascular portion appears to move slightly in the opposite direction. Helmholtz, after showing in a very complete manner how the shadows of the arteries cause the effects which are seen, remarks that the appearance of the central portion is undoubtedly not produced in the same manner. It will be noticed that the vascular tree encroaches on the central portion on the side opposite the light, whilst above and below it only touches it ; on the side nearest the light there is an interval between the two. All the appearances remain the same whether the light be at the internal

or external angle of the eye. The reason of this is that the vascular system is situated anteriorly to the portion of retina which gives rise to the spotted appearance. The portion of retina which gives rise to this appearance exactly corresponds to the non-vascular portion of the retina. When I have repeated this experiment, and I have found the light from an acetylene lamp concentrated on the sclerotic answer admirably, the central portion has first appeared dark, but in addition to the vessels concentric bluish-violet coloured waves are seen. These waves appear as bluish-violet coloured circles of light which roll inwards from the outer part of the field of vision. They occupy the whole circumference, and appear as steadily diminishing circles. Each succeeding circle reaches further towards the central portion of the field of vision until one touches it. It then appears to break up into a star-shaped figure and becomes much brighter. This is then replaced by the spotted appearance already mentioned.

J. H. Nuel [1] and L. Wolffberg [2] have come to the conclusion from careful measurements that the appearance of the central portion corresponds to the mosaic formed by the cones of the fovea.

2. *Illumination through Cornea.* The second method of seeing the blood vessels of the retina is similar to the first, only the light is allowed to enter the eye through the cornea. The observer being in a darkened room and the eyes being directed forward, a candle is moved

[1] *Arch. de Biol.* T. iv. 1883. [2] *Arch. für. Augenhl.* xvi. 1886.

backwards and forwards either at the side or above the eye. The fine vessels and capillaries are not seen so well in this method as in the other two. In the central portion several observers have seen a bright disc circular or elliptical in shape, others have been unable to see the whole of the disc. In ordinary circumstances I only see a portion of the disc, it is bordered on its outer side, the side nearest the light, by a dark crescent and external to this is a bright crescent which is much brighter than any portion of the interior of the disc. When the light moved upwards the bright crescent also appears to move upwards. When I move the light much more quickly and with a circular movement I am able to see the whole of the disc. The appearance then often changes to that seen in the first method, this appearance being generally preceded by the pale bluish-violet circles. I often find that the central portion appears dark and not light. I find that the central portion appears dark with red light, whilst with green light it appears bright and spotted, the rest of the field also appears brighter.

3. *Illumination through Pinhole.* The third method of seeing the retinal vessels consists in viewing a large uniformly illuminated surface, as for instance the sky, through a pinhole aperture which is moved rapidly backwards and forwards in front of the eye. The capillaries are very clearly defined, dark on a light ground. In the centre there is a portion free from

vessels and bounded by the convex side of the loops of the capillaries.

4. *Illumination when the Retina is Specially Sensitive.* I find that I can see the retinal vessels very clearly if on opening my eyes in the morning on awaking I immediately direct them to the white ceiling. The larger vessels appear very black and distinct. The central portion of the field of vision appears as an oval black

Fig. 8.

patch and light appears to invade this patch from without inwards. The effect is only momentary.

III. Currents Seen in the Field of Vision not due to the Circulation.

1. *Currents Seen with One Eye Partially Covered.* If one eye be partially covered with an opaque disc whilst both eyes are directed forwards in a not too brightly illuminated room and special attention be paid to the

covered eye an appearance of whirling currents will be seen with this eye. (See Fig. 8.) These currents appear to be directed towards the centre, and have a very similar appearance to a whirlpool. On closing both eyes all the portion in which the whirling currents are seen appears as dull purple. These currents cannot be due to vessels, because we know that the centre of the retina, corresponding to the point where the greatest movement is seen, is free from vessels. The appearance is also very different from that of the movement of blood in vessels. The experiment succeeds best if the eyes have been previously exposed to a fairly bright light. An opaque disc in a spectacle frame suffices admirably, a certain amount of light being allowed to enter the eye from the periphery.

2. *Currents Seen in the Light with One or Both Eyes Open.* It is easy to see the currents at almost any time on regarding fixedly a not too brightly illuminated surface. I find that it is better to use only one eye, but they can be seen with both eyes open. The first appearance which is always visible to me is a star-shaped figure corresponding to the region of the fovea. (Fig. 9.) When seen with one eye this star has eight rays. It is due to the structure of the lens. There appears to be rapid circular movement behind this star—that is, the

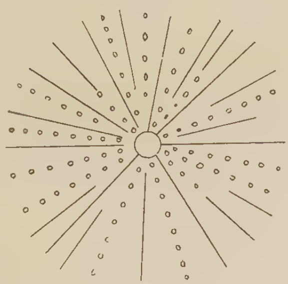


FIG. 9.

movement appears to be further off in the field of vision —like a top spinning, or a catherine wheel, the rays of the star remaining always visible and stationary. The movement is from left to right with the right eye and

Fig. 10.

from right to left with the left eye. The field of vision then becomes dark, and the movement spreads until it covers the whole region corresponding to the yellow spot, and the currents in this outer portion form a network with wide meshes. (Fig. 10.) The currents seem to proceed from four main places of entry, two horizontal

and two vertical. The movement is at first slow and then gets more and more rapid, especially in the centre.

3. *Currents Seen in the Dark.* Currents can be seen in the dark which correspond in their general character to those seen in the light. The whirling in the centre is usually very noticeable. Generally pale bluish-violet circles form in the periphery, and these gradually contract and advance on the centre of the field of vision. When the circle reaches the centre it breaks up into a star-shaped figure and becomes much brighter. This is then succeeded by another contracting circle.

4. *Currents Seen through Yellow-green Glass.* I see these currents with yellow-green glass when the eye has become fatigued by looking through the glass, the whole field becomes dark and the whirling currents are seen. The general form remains the same. Fig. 10 should be compared with the drawing given by Exner[1] as the figure seen entoptically with red light. It is evident that he saw the same figure, but he does not say anything about movement, this is probably due to the fact that the figure is very fugitive with red light. The position of the currents in the outer part of the field of vision seems to change continually

5. *Currents Seen with Intermittent Light.* If when regarding a rotating disc composed of black and white sectors we note the time when the fine flicker is most marked and keep the eyes steadily fixed on the disc, the field of vision often becomes dark red and we see a

[1] *Pflüger's Arch.* i. S. 375-391, 1868.

visual quality, colour and brightness of the background from which they come. Ferree considers that eye movement is the chief or sole factor in the formation and direction of these currents, but I see them quite clearly with my eye quite still, and the whirling in the centre is not appreciably different when the eye is moved from one point to another.

9. *Effect of Moving Material on Centre of Retina.* On opening one eye on awaking in the morning and looking at the ceiling the central portion is seen as an irregular, circular, rhomboidal or star-shaped black spot. On closing the eye again a bluish violet circle appears at the periphery or middle of the field of vision, contracts, and then after breaking up into the star-shaped figure and becoming brighter disappears, to be followed by another contracting circle. If the eye be opened when the star figure has formed in the centre it will appear as a bright rose-coloured star, much brighter than any other part of the field of vision. If, however, we wait till the star has broken up and disappeared before opening the eye, it will be found that only a black spot is seen in the centre.

10. *Time of Interval between Contracting Circles.* I have timed the contracting circles with a stop-watch and find that the interval between two is very irregular. They may follow each other regularly at intervals of one or two seconds and then cease. They are not apparently synchronous with the pulse or respiration, and they still go on moving when I hold my breath.

11. *Effect of Light on Size and Colour of Currents.* When the light which is entering the eye is diminished a broad current narrows to a thin line. The circles in these circumstances contract to thin lines which are at an angle to the circumference of the circle and are not joined together. The colour of the circles and currents is with very dim light bluish white, with more light bluish violet, and as more light is added the colour becomes redder and redder until it is finally rose.

12. *Effect of Light on the Star Figure.* The central part of the star figure is seen with dim light. If more light is allowed to enter the eye the star figure changes into a rhomboid, exactly as it did when seen by pressure and the pressure was increased.

The currents and star can be seen very well in a dim light, as for instance that of a white blind illuminated by moonlight.

On moving the open fingers before one eye, the labyrinth of whirling currents is well seen with the star figure in the centre. The movement continues for several seconds after the hand has been removed from the eye.

13. *Effect of Moving Material on Appearance of Small Lights.* If a small light be looked at in a dark room, as for instance that coming through the smallest diaphragm of my colour perception lantern, which represents a $5\frac{1}{2}$ inch bull's-eye railway light at 1000 yards, care being taken not to move the eye, the contracting bluish violet circles will be seen. The colour of the circles is the same for white light or any coloured light. When it reaches

the centre the light brightens. If the circles stop the light disappears.

14. *Illusion of Moving Light.* In many cases in repeating the above experiment the light will appear to move. This is particularly noticeable with red light, but may be seen with any other. The light appears to move until it apparently comes close enough to be grasped by the hand when it is really 20 feet off. I have the impression the whole time that I am looking straight at the light when it is really falling upon a peripheral part of the retina. The other closed eye is still directed straight at the light, and on opening this eye two images of the light are seen, which rapidly coalesce, the peripheral image joining the central one. The light appears to move as if some substance went downward by gravity: when the head is upright the image appears to move upwards, when bent to one side the image appears to move in the opposite direction, but appears to approach during its movement.

15. *Phenomena Seen on Closing one Eye.* If in the morning on awaking I look at the white ceiling with both eyes the black spot appears and disappears as usual. If I then close one eye, bright curved lines appear in the periphery of the field of vision and the centre becomes bright.

IV. Appearances due to the Pigment Cells of the Retina.

1. *Visibility through Intermittent Light.* Charpentier [1] states that if the fingers be slightly separated and then

[1] *Compt. Rendus*, xcii. pp. 335-357.

when the other eye is shut the fingers moved rapidly backwards and forwards whilst the gaze is directed towards the blue sky, the field will be covered with dark purple-violet hexagonal figures, there being a light interval between each. I agree with Wolffberg that these figures correspond to the hexagonal pigment cells. They cover a much greater area of the field of vision than corresponds to the fovea and have a diameter at least four times as large as that of the circles seen in the region of the fovea.

The following experiment shows almost certainly that the appearances are due to the pigment cells: Whilst my right eye was fixed on a gas flame shielded by an opal glass globe I moved from side to side in front of the eye a piece of black cardboard with a vertical slit of an inch long and a quarter of an inch wide. On moving this moderately quickly the whole gas globe appeared pure green instead of yellow and covered with hexagonal figures, each with a brighter circular spot in it. Between these hexagons were little red curved lines in which there appeared to be rapid movement. These red lines were between but did not encircle the hexagons. Increasing the rapidity of the movement of the cardboard did not alter the appearance of the phenomenon. (See Fig. 12.)

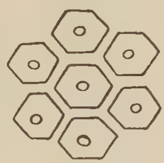


Fig. 12.

2. *Visibility when the Retina is Specially Sensitive.* I can also often see hexagons of the same size on

awaking in the morning, but they are light with a dark interval between each.

V. The Effect of the Blood in the Vessels of the Retina.

It occurred to me that if we could suddenly be made conscious of the absorption of the green rays by the blood, since the cones in the vascular area are influenced only by those rays that pass through the blood, the colour of the absorbed rays would appear as a contrast effect in the field of vision corresponding to the non-vascular portion of the retina. The effect can be shown in two ways.

1. If we look through a blue-green glass at a uniformly illuminated white surface, as for instance a white cloud in the sky, for about 30 seconds, on removing the glass the whole of the field of vision appears rose, with the exception of the centre corresponding to the central non-vascular portion of the retina; this appears bright green. The colour of the green is pure green and not a blue-green similar to the colour of the glass. It will be noticed that there is a brighter portion forming the star figure already described (Fig. 10). The colour of the surrounding field of vision is rose and not red, the complementary of the blue-green glass. As the colour seen is very similar to that of the visual purple it might be thought that this was the cause of the phenomenon. The green area, however, corresponds to the non-vascular portion of the retina and not to the rod free portion, and

I have never seen this green colour in conditions in which visual purple phenomena become evident.

2. On looking at a sky which is obscured by a white fog for 20 seconds with one eye, the other being closed and covered with the hand: on removing the hand from the covered eye after opening it, the centre of the field of vision is seen as pure green, the star-shaped figure being seen as in the previous experiment.

The surrounding part of the field of vision does not change colour, but appears white, as it did before opening the covered eye. The light transmitted through a white fog contains a preponderance of red rays, as may be seen by viewing a light or the sun through it: both appear much redder than usual.

VI. Visual Phenomena caused by Pressure on the Eye.

If gentle pressure be made on the front of one eye with the palm of the hand a star-shaped figure with four rays is seen, bright on a dark ground. It is similar in every respect to the central part of Fig. 10.

When both eyes are covered with the hands and more prolonged pressure is made on the right with the palm a rhomboidal figure is seen. This is formed through the filling up of the spaces between the rays of the star, and the points of the rhomboid correspond to the extremities of the rays of the star. In addition bright lines are seen moving in a whirling fashion from the periphery towards the centre. The appearance is exactly the same as that of the currents I have already

described. It is evident that Helmholtz saw the phenomena as I do, as his description[1] will apply admirably to the currents and star figure I see on prolonged pressure.

VII. Various Effects of Intermittent Light.

If we note the effects of intermittent light upon the retina it will be found that the phenomena which are seen apparently change. All are phenomena which have been described, but they are seen at different times. For instance, if the open fingers be moved rapidly before one eye whilst the vision is directed towards a white cloud in the sky, we may see in succession some or all of the following, but not necessarily in the order given.

1. Loewe's ring, Maxwell's spot and the fovea.
2. The appearance of the blood vessels of the retina.
3. The vascular network due to the capillaries of the retina. The non-vascular portion is seen as a uniform white circle surrounding a granular disc.
4. Appearances due to the yellow pigment of the yellow spot.
5. The star figure and currents.
6. Appearances due to the pigment cells of the retina.
7. The eight-rayed star due to the lens.

VIII. Effect of Blow on the Eyeball.

I was suddenly thrown off my bicycle by riding over an object in the road and struck the outer side of my right eyeball on the ground. A bright rose-purple light

[1] *Physiol. Optik*, ii. Aufl. S. 237.

was visible in the corresponding part of the field of vision for several hours after the accident.

IX. Influence of a Light on Surrounding Regions of Retina to that which is Stimulated.

If a light be looked at steadily with one eye when it has dark surroundings incapable of reflecting any light, it will appear to be surrounded by a halo made up of numerous rays of the same colour as the light. If the light be white the rays look like thin rivers running towards the light. Each point of these rivers becomes alternately rose and green, that is to say a rose-coloured particle appears to be followed by a green one, which is again followed by another rose particle. On covering the eyes with the hands after shutting them a pure green patch is seen corresponding to the light. This is surrounded by rose corresponding to the rays. The rose gradually encroaches on the green, which does not change colour. On opening the eyes a bright rose patch is seen, which does not change colour but gradually fades away.

X. Red Spot in Field of Vision.

When in darkness with the hands over the eyes I often see a small circular red spot in the centre of the field of vision. When the attention is fixed upon it, it swells out and becomes colourless.

XI. The Appearance of the Blind Spot in the Field of Vision.

On waking in the morning and viewing the ceiling with one eye I have seen the blind spot as a clearly

defined black area with the images of the blood vessels of the retina spreading from it as branching black lines. This appearance can also be seen when intermittent light is used before one eye. The fact is important as showing that the sensation of black can be obtained in a region in which there are no sensitive elements in the retina.

Interpretation of the Phenomena.

On the theory given I explain these phenomena in the following way. The currents seen are currents caused by the liquid sensitized by the visual purple flowing into the external fovea. When there is visual purple in the fovea this is the most sensitive part of the whole retina, but when there is none there time must elapse before it can diffuse into the spot.

I have three specimens prepared by C. Devereux Marshall showing the retinae of monkeys from the outer side and the arrangement of the rods and cones. The appearance of the cones of the fovea is exactly the same as the entoptic appearance of this central portion. The cones appeared as circles arranged in lines nearly at right angles to each other with a slight curve towards the centre of the fovea. I found the same with a human fovea, only the cones were smaller than in the case of the monkey. On examining the external surface of the retina of a monkey there appeared four slight depressions leading to the larger depression of the external fovea. These depressions correspond to the four main branches seen in the subjective phenomena, and would appear to

be channels to allow of the easy flow of the visual purple. It occurred to me that if this were the case we should obtain evidence of them in cases where the outflow from the retina was obstructed, as by tumour. I find that this is the case, the star-shaped figure given by Sir Victor Horsley in his paper on tumour of the frontal lobe[1] is almost exactly the same as that seen subjectively.

All the drawings are for my right eye.

The web-like appearance seen subjectively corresponds to the cone distribution of the retina as viewed from its outer side, the portions occupied by rods appearing as dark spaces.

The yellow pigment in the yellow spot on the theory I have given should have a similar function to the yellow screen in photography.

[1] *Brit. Med. Journ.* p. 556, 1910.

CHAPTER XV.

BINOCULAR VISION.

When the two eyes are used together, vision is much better than with one eye alone. In this chapter we are concerned with the details of the differences in vision with two eyes over that with one.

The Visual Fields.

The whole of the sensations received from the external world by one eye is the visual field for that eye. The visual fields for both eyes are not the same, and the visual field for each eye varies with certain conditions, as for instance, the size of the pupil and the position of the eye. The visual field for both eyes together is much larger than for one alone, and the central portions of the fields of both eyes overlap, therefore in the visual fields for both eyes certain objects are only seen with the right eye, others only with the left, and those occupying the centre with both.

Corresponding Points.

If the retinae of both eyes be placed one over the other so that the foveae and similar quadrants correspond,

then all those points which lie over each other in both retinae are called corresponding points. When the corresponding points of the two retinae are stimulated by light, the stimulus in each case is usually referred to the same portion of the field of vision.

It will be noticed that the foveae of the two retinae are corresponding points and that the blind spots are not.

When in ordinary circumstances both eyes have been directed to an object which is then seen singly, one of the eyes is moved with a finger, two images of the object are immediately seen instead of one, because the images of the object fall on non-corresponding points of the two retinae.

A special function of the movements of the eye is to bring the object looked at upon corresponding points of the two retinae. The eye moves in the orbit in a similar way to a ball and socket joint. The movements of the eye are carried out round a centre of rotation which has been ascertained to be 13·5 mm. behind the anterior surface of the cornea. This is not quite 2 mm. behind the geometric centre of the eye, which, however, is not a sphere.

When the eye is directed to a fixed point a line drawn from this to the centre of rotation and the centre of the fovea is called the visual axis. When the eyes are directed straight forward, the visual axes are parallel but on looking at any near object the visual axes become

convergent, the convergence increasing in proportion to the nearness of the object.

The corresponding points have been ascertained in a number of different ways, and it is found that they vary slightly with individuals and are not exactly represented by one retina being placed over the other. Purkinje [1] marked out the corresponding points of the two retinae by means of pressure phosphenes. Helmholtz gives the corresponding points and lines in the visual field as follows :

1. The fixation points of both visual fields, especially that corresponding to the middle of the foveae.
2. The horizon for both eyes.
3. The vertical meridian to the horizon.
4. Points in the vertical line which are at equal distance from the corresponding points of the horizon.
5. Points in the horizon which are at equal distance from the fixation points.
6. Points of both visual fields which both in height and breadth have a similar angle.

Horopter.

The horopter is a line or surface formed by the points in the field of vision, the images of which would fall on corresponding points of the retinae.

[1] *Physiol. d. Sinne,* vol. i. 142 f. 1819.

The Movements of the Muscles of the Eye.

The eye is moved

inwards	by the	Rectus internus.
outwards	,,	Rectus externus.
upwards	,,	Rectus superior. Obliquus inferior.
downwards	,,	Rectus inferior. Obliquus superior.
inwards and upwards	,,	Rectus internus. Rectus superior. Obliquus inferior.
inwards and downwards	,,	Rectus internus. Rectus inferior. Obliquus superior.
outwards and upwards	,,	Rectus externus. Rectus superior. Obliquus inferior.
outwards and downwards	,,	Rectus externus. Rectus inferior. Obliquus superior.

Listing's Law.

It will be noticed that in addition to movements of the eyes upwards and downwards, outwards and inwards, or in any oblique direction there is another possible movement of the eye, and that is one similar to a cart wheel moving on its axis. Listing's law is that when the eyeball moves from the primary position to a secondary position the angle of rotation in the secondary position is the same as if the eye had been moved round a fixed

axis perpendicular to both the first and the second positions of the visual line. If this were not the case images would fall on non-corresponding points of the two retinae. The experimental proof is usually given as follows: If on a wall there be placed a sheet ruled with a number of horizontal and vertical lines and an after-image of a cross made by a vertical and horizontal line at one of the angles be looked at, it will be found that the after-image of this cross will also consist of a vertical and a horizontal line. It will be found that the vertical line of the after-image will correspond with the vertical lines on the paper and the horizontal line of the after-image will correspond with the horizontal lines on the paper as the eyes are moved up and down over the paper.

When double images fall upon corresponding points they combine to form a single image just as if the images had been received from one object. If two coins be taken and placed on a table so that the heads of each correspond, double images of each can be obtained by looking at an object further in the distance, two of these images can be made to combine by varying the positions of the coins and the object which is being looked at. We shall then have three images of the two coins, two single and one combined image.

The eyes usually move together, even when one of them is blind. This is not invariably the case, as is shown by the experiment of the moving light given on page 98.

Binocular Projection.

In binocular vision the visual lines are apparently shifted on either side half an interocular space, so that the visual line now occupies a position midway between the two eyes, the visual line being moved for the left eye half an interocular space to the right and that of the right eye half an interocular space to the left. In binocular vision we see as if we had one eye occupying a position midway between the two eyes. This is apparent on looking out through a pair of spectacles; we appear to be looking through one large glass with its centre midway between the two eyes, the internal portions of the rims of both glasses seem to have disappeared. If with the nose closely pressed against a looking-glass we look away as if into the distance we apparently see one eye in the median position looking at us out of the glass.

Binocular Contrast.

The perception of relative difference is as important in binocular vision as it is in monocular vision. This accounts for the predominence of contours and sharply marked black or white lines in binocular vision.

Double Images.

As the two foveae are corresponding points, it follows that if the eyes be directed to an object in the distance and at the same time an intervening object be regarded, it is not possible for the intervening object to fall upon

corresponding points. A simple example of this is the case of a gun which is sighted for a certain object: the sight must either be used for the right eye or for the left. It follows from this that a large number of double images are formed, which would be very troublesome if they were noticed in ordinary life. As a matter of fact, it is difficult to see these double images without specially looking for them. The chief reason for this is that one eye is principally used in any visual act. One eye usually has a preponderating influence but, in most cases the eyes are used alternately, and it is often difficult to ascertain to which eye the image which is seen belongs without closing one of the eyes. If a numbered scale be placed at a distance of fifteen feet from the observer and on a table midway between it and the observer be placed an object with a sharp triangular point, the fact mentioned above can be illustrated. If the observer look at the triangular point with both eyes open, he will see that it is quite easy for him to make it correspond with a particular figure on the scale. At the same time he will not see any trace of a double image even when this is carefully looked for; at least this is true for a large number of persons. If, however, the dominant eye be closed, the triangular point no longer corresponds to the previous figure on the scale but springs up in another portion of the field of vision. From this it appears that a large number of double images are in ordinary circumstances suppressed.

Fig. 14 illustrates the formation of double images.

Both eyes are supposed to be directed to point A, and this point forms an image on both retinae at corresponding points—namely, the centres of the foveae of both eyes. B1 and B2 and C1 and C2 show the positions on the retinae of the points B and C whilst the point A is being observed. It will be noticed that the images fall on disparate points of the retina. The centre portion of the figure shows the projection in space of the double images.

Though double images are seen when one eye is moved with the finger whilst both are directed at one object, the essential point in the formation of the double images is that the whole apparatus is dislocated whilst the eyes are open and that images are falling on non-corresponding points. One eye may be moved independently of the other without the formation of double images or change in their localisation in space. If an after-image be formed and the eyes closed and covered with the hands, the after-image is seen single and not double when one eye is moved independently of the other with the finger. Of course in this case the retinal stimulation is the same, the corresponding points of both eyes being stimulated as before, the only change being in the movement of one eye.

The improvement in the perception of relative distances with two eyes over one is shown by Hering's ball experiment, in which small balls of various sizes are dropped in front or behind a vertical thread; with two eyes it is very easy to tell whether the balls are dropped in front or behind the thread; it is very difficult with one eye.

Retinal Rivalry.

When two dissimilar pictures are combined in a stereoscope there is a tendency for one or other of them to prevail in the field of vision. A continued alternation takes place, first one is seen almost entirely, then a combination of the two and then the other. This will even occur when such a very marked object as a thick black cross is combined stereoscopically with a network of black lines on a white ground. At one moment the black cross will be seen on a white ground, then a black cross on a network and then the network on a white background, the black cross having entirely disappeared. The same will be found in combining horizontal and vertical lines, and even when a broad black horizontal stripe is combined stereoscopically with a broad black vertical stripe on a white ground. When the two black stripes are combined and the centres are fused, these appear black, but the adjacent portions of the cross appear much lighter, increasing in darkness at points further away from the black centre. One or other of the arms of the cross will become lighter and tend to disappear or actually disappear at intervals. When a white pattern on a black ground and a similar pattern in black on a white ground are combined stereoscopically, the field does not appear a uniform grey, but an object in relief, either black on a white ground or white on a black ground will be seen alternately and successively, and varying combinations of the two. When an object outlined in black is combined stereoscopically with the

object represented entirely in black it appears almost the same as if two outlined figures had been combined, the centre appearing almost as white as the surrounding background.

The dominance of one eye or the other is particularly noticeable when stereoscopic pictures of a simple object painted in different colours, as for instance red and blue, are placed in the stereoscope. The object is usually seen in one or the other colour and an alternation takes place, the object may first appear blue, then purple, and then red. Again, if two pictures be combined in a stereoscope in which one is quite different from the other, as for instance, a cage on one side and a bird on the other, it will be noticed that the two pictures are not completely fused as they would be by combining the picture of the bird with that of the cage. The bird will undoubtedly be seen within the cage, but the bars of the cage will be indistinct or missing where they would if they were fused touch the bird or run right across it.

The same is found with many even with horizontal and vertical lines. A series of vertical lines being placed on one side of the stereoscope and a series of horizontal lines on the other, in the combined picture the horizontal or the vertical lines will predominate and an alternation will take place.

Single Vision with Disparate Points.

When images of two objects fall upon widely disparate points double images are formed, but when there is

only slight disparation a single image is formed. The amount of disparation which will allow of single vision has been estimated by Volkmann.[1] He combined stereoscopically two sets of parallel lines; both lines of the first pair were at a fixed distance from each other, and of the second pair one was fixed and the other moveable, so that the distance between these two lines could be varied at will. (See Fig. 13). The important fact in this experiment is that when the lines are fused with disparate points their position in space appears to be different; one line appears to be raised above the other in the stereoscopic combination, and we have an appearance of stereoscopic relief. Wheatstone was of opinion not only that we can have single vision with disparate points, but that we can have double vision with corresponding points. This has been denied by many observers, but is still a subject of discussion. He showed that if a thick vertical line be drawn on one sheet of paper and a thin vertical line with a thick line running diagonally across it on another sheet of paper (see Fig. 15): when these are placed in the stereoscope the thick diagonal and vertical lines combine into one and a thin line is seen running vertically through it. The important point in this experiment is that the thick line appears to stand out from the paper. Spearman also holds the same opinion, which of late years has been steadily gaining ground. He shows that if two figures, like Fig. 16, be combined in the stereoscope two definite

[1] *Arch. f. Ophth.* 1859, Bd. v. Abth. 2, S. 1.

F's will be seen. I find that I can see these F's for several seconds at a time, though there is a tendency for the thin vertical line on the right to move, and we have the curious spectacle of an object moving plainly backwards and forwards although all the time the place of retinal stimulation remains unchanged. If objects seen by corresponding retinal points necessarily appeared in the same direction, then, when the thin lines of the left of A and B respectively combined into L, the other two thin lines would necessarily appear as ⊥: for the distance between the two vertical thin lines is equal to the distance from the left extremity of the left horizontal thin line to the centre, not the left extremity of the right horizontal thin line.

The Perception of Relief.

Though the perception of relief is much more complete when both eyes are used, there is undoubtedly perception of relief with only one eye. When the visual axes are parallel and objects in the far distance are being regarded, the visual fields of both eyes are almost exactly similar, and the perception of relief is the same with one or both eyes together. Objects appear in relief when viewed by an electric spark, and in this case there is no time for any movements of the eye so that the eyes are brought to converge on any particular object. The perception of relief either monocularly or binocularly is practically the same for one or both eyes when the objects are beyond a certain distance from the eyes.

The perception of relief in these cases depends almost entirely upon the light and shade of the object and the judgment formed therefrom as to whether a solid or plain object is being observed. I have on many occasions been quite unable to decide whether a lantern slide was being shown or a projection by means of an epidiascope. Coloured photographs of crystals, for instance, have had such a very solid appearance, just as if the actual objects were being shown. It is the same with many of the coloured pictures which are exhibited by means of the cinematograph, the appearance of relief is as striking as it is when pictures are viewed in the stereoscope. In the perception of monocular relief the isolation of the object is important, a photograph viewed through a magnifying lens with one eye appears in higher relief than without the lens, and this appears still more striking when viewed with one eye through a stereoscope when the picture occupies the greater part of the field of vision; the relief is even more marked when both eyes are open and one is viewing a sheet of white paper which is placed on the other side of the stereoscope. Wheatstone [1] states that when a perspective of a building is projected on a horizontal plane, so that the point of sight is in a line greatly inclined towards the plane, the building appears to a single eye placed at the point of sight to be in bold relief, and the illusion is almost as perfect as in stereoscopic relief.

Two different images are undoubtedly necessary for

[1] *Phil. Trans.* 1838, p. 381.

binocular perspective. If two horizontal wires be looked at with the head erect from a distance of about twenty yards when they are about five feet from each other the images are the same for each eye, and it is difficult to say how far apart the wires are. When the head is turned to one side the difference in position is at once evident.

When the visual axes are not parallel, the visual fields become more and more dissimilar in proportion to the nearness of the object and the convergence of the visual axes. If for instance a cube be looked at when it is placed on a table at a distance of three feet from the eyes, and so that one side of the cube is only visible with the right eye, it is quite obvious that the visual impression for the right is quite different from the left, as may be seen by carefully observing the cube whilst first the right eye and then the left is closed. Now if the cube be regarded in relation to the two pictures it will be noticed that the picture formed by one or other eye has a dominant influence in relation to the appearance of the cube as viewed binocularly. This is particularly noticeable with regard to surrounding objects. If, for instance, the exact point of correspondence between one corner of the cube and some noticeable portion of some other object situated some six inches away be noted carefully, it will be found that the correspondence of the two will be for one eye only, as can be seen by closing first one eye and then the other. It will be found that the double images for one eye have been entirely suppressed, and it is difficult to see them even with the most careful

observation when the objects are not too far apart. A point which will immediately strike the observer when he closes first one eye and then the other whilst viewing the two objects is that the striking appearance of depth and distance disappears when only one eye is used. It now becomes very difficult to say with any degree of certainty how far the two objects are apart. The perception of relief and depth therefore seems to be intimately connected with single vision with disparate points.

The perception of binocular relief is, however, independent of double images and the stimulation of disparate points, provided that the object presents images to the two retinae similar to those which are presented by an object in the field of vision. This can be shown by taking a pair of stereoscopic photographs in which the point of sight is at the centre of each and cutting them vertically in two, and then having pasted the left half of the left photograph on the left side and the right half of the right photograph on the right side on white or black cardboard at an appropriate distance so that there is no overlapping when placed in the stereoscope, a picture in striking relief is obtained when combined together in the stereoscope. In this case it will be noticed that there is no portion common to both fields of view. In each case the overlapping portion is combined with white. It seems probable that this is how binocular vision takes place in ordinary circumstances. If an object in high relief, as for instance a vase or the face of a

person be viewed at a short distance and one particular point fixated, it will be noticed that the right eye dominates the right side of the field of vision and the left eye the left side. The image seen is almost entirely that of the right eye for the right side and that of the left eye for the left side, as may be proved by noticing the relations of surrounding objects and closing first one eye and then the other alternately.

The same is found when pictures are carefully examined in a stereoscope. If the relations of two objects be carefully noted, as for instance the exact distance of the spire of a church from an adjoining house, when this is markedly different in the stereoscopic pictures for the right and left eyes, it will be found that the distance noted binocularly corresponds for either one of the two pictures, but is not a position which would correspond to a fusion of the two. The conditions in which fusion takes place will be shortly described. In ordinary circumstances a large number of double images are completely suppressed. Double images appear when the mind is not able to project externally an object which would produce the two pictures which are falling upon the two retinae. This is strikingly shown by Fig. 19. If these be combined in the stereoscope it will be found that first two of the squares combine into one and double images are seen of the two others. Then suddenly both pairs of squares will combine to form two squares, one square appearing much nearer and smaller than the other, but like it situated in the median line.

When the two halves of stereoscopic pictures are combined in this way it will be noticed that they blend perfectly and that there is no retinal rivalry. (See Fig. 18.) When in the stereoscopic photographs viewed in the ordinary way there is some incongruous object, as for instance a flaw in the photograph or two objects which do not correspond, the perception of relief is actually better with the divided photograph.

If a careful comparison be made between stereoscopic pictures viewed in the ordinary way and the halves of stereoscopic pictures as described above, it will be found that when there is any superiority in the ordinary stereoscopic photographs it is when there is a fusion of a line or lines in the foreground. In some cases the perception of relief is much better with the divided photographs and with objects which appear in very strong relief, as for instance in some of marble columns and stalactites in a cave, that is to say rounded surfaces. In many of these cases it will be found that the ordinary stereoscopic photographs are very hard to fuse. It would appear therefore that the perception of such objects in relief in ordinary binocular vision took place, not by fusion, but by suppression of the right eye image on the left side and the left eye image on the right side ; the two halves of the image being combined at the point of fixation. The inversion of relief produced by the pseudoscope can be seen with the divided photograph.

It will be noticed that in the case of a rounded object, as for instance a sphere or rounded column which is

viewed binocularly, only a solid object could give rise to the two images which are formed upon the two retinae irrespective of the duplication of impressions, that is to say when only the right and left halves are considered. The mind therefore projects the image of an object, capable of producing both impressions, in the field of vision.

Binocular vision itself, apart from any double images, tends to give rise to a perception of solidity and relief. If two photographs taken from the same negative be placed one on either side of the stereoscope a striking appearance of relief is obtained, though the photographs are not stereoscopic photographs and no double images are formed. If a stereoscopic photograph of a scene be placed in the stereoscope and viewed in the ordinary way the usual striking appearance of relief is obtained. If now, whilst the eyes are still looking at the photograph, a sheet of white cardboard be dropped over one of the photographs so as to entirely occlude this photograph and only present a white surface to one eye, a striking appearance of relief remains. This fact may be emphasised even more by altering the experiment in the following way: If the cardboard be placed so that only half of one photograph be occluded, a careful comparison can be made between the upper and lower halves of the combined visual field. It will be noticed in many cases that the appearance of solidity is nearly as great in the portion which is being viewed with only one eye as with that which is being viewed with both. It will be noticed

that when there is one picture in the stereoscope and a white blank on the other side, that the appearance of solidity is greatly diminished when the eye receiving the impression of the white surface is closed. It is probable that the more striking appearance of solidity of objects in the distance when viewed with both eyes than when viewed with one must be due to the duplication of similar impressions, as when the visual lines are parallel or nearly parallel the difference between the photographs on the two retinae for objects in the distance which occurs on account of the interocular interval is very small.

Straub has shown that perception of depth can be obtained with one eye by stimulating adjacent points successively.

The influence of the movements of the eye on the perception of relief has been the subject of much discussion, but numerous observers have shown that the perception of relief is quite independent of the movements of the eyes, as indeed is shown by the stereoscope.

Binocular Fusion.

It is obvious that the fusion of images on the retina does not account for binocular vision. Where images of the same object fall upon corresponding points these are fused and appear single; this is particularly the case for images falling upon the centres of the two foveae. When the images do not fall upon corresponding points there is suppression and selection. In certain cases

images which fall on non-corresponding points may be fused, but the appearance of the object is quite different from that which is found when images fall on corresponding points. If stereoscopic pictures of a truncated cone be placed in a stereoscope, a very definite picture of the truncated cone in high relief is obtained. Let us suppose that the truncated cone is placed so that the smaller end faces the observer. On comparing the stereoscopic pictures it is seen that they are quite different for the right and left eyes, the small circle appears with the right eye to be much further away from the base than it does with the left eye. If the pictures be carefully examined in the stereoscope when viewed binocularly it will be noticed that there has been a complete fusion of the two images.

There has been much discussion as to whether there really is fusion in these cases or whether each point of the image is combined successively whilst other points are seen double. There can be no doubt that there is actual fusion, when double images appear the perception of solidity greatly diminishes. Without experience no one could tell in many cases the figure into which two stereoscopic pictures will combine, as for instance two slanting daggers which combine into one dagger which apparently stands out from the paper; or two other daggers of the same shape but of different size which combine into one which appears to stand out diagonally across the paper. It may be noted that the images on the two retinae of the object as seen would be similar

to the two stereoscopic pictures. (See Fig. 17). It would appear therefore that fusion takes place when the mind is able to project externally the images of an object in a position which would give rise to the images on the two retinae similar to the two stereoscopic pictures.

In those cases in which there is fusion of two halves of stereoscopic pictures presented to each eye it is obvious that the same mental process takes place, because in this case no double images are formed. If the stereoscopic pictures representing a truncated cone be divided, the small circle being divided exactly in the centre or three circles arranged similarly, two or three perfect circles will be seen when combined stereoscopically in the manner previously described.

It might be thought that the explanation of fusion in binocular vision was to be found in a common cerebral centre for each pair of corresponding points, and indeed this was the view of many of the older physiologists. There are, however, many facts which are quite inconsistent with this view, particularly those ellicited by the researches of Sherrington,[1] Macdougall,[2] and Hartridge.[3] The following facts are against the view of a common cerebral centre for both corresponding points. Objects do not appear brighter or only slightly brighter with both eyes than when viewed monocularly. If there were a common cerebral centre the results should

[1] *Journal of Psychology*, 1904, p. 26. [2] *Brain*, 1911, p. 371.
[3] *Journ. of Physiol.* 1915, p. 47.

be the same as if one eye were stimulated with a light of twice the intensity. In certain conditions the additional stimulation of one eye with light not only causes no sensation of increased brightness but the reverse This is illustrated by Fechner's paradoxical experiment. One eye is directed to an illuminated surface, as for instance a sheet of white paper, whilst the other eye is closed. If the closed eye be suddenly opened behind a sheet of smoked glass, the field of vision will appear distinctly less bright. In this case the additional stimulation of the second eye with the light which passes through the smoked glass adds nothing to the sum of the stimulation.

If an after-image be formed in one eye and allowed to die away, the eyes being shielded from all light, this after-image may be revived one or more times by momentarily allowing light to enter the eye. This may in certain circumstances be accomplished by allowing light to enter the other eye, but the effect is not nearly so marked as when light is allowed to enter the eye which is primarily the seat of the after-image.

When one or both eyes are stimulated with an intermittent light of a given intensity, the disappearance of flicker is almost exactly the same for one or both eyes together or alternately on corresponding points of the two retinae.

The well-known facts of binocular rivalry and fusion are against the view of a common centre; we have every grade of fusion from complete fusion to the entire

suppression of one image. The fact that single vision is not confined to corresponding points but disparate points may be united in certain circumstances and the union of images falling upon disparate points causes an appearance of depth.

The Predominance of Contours is an important factor in binocular fusion. If there be placed in a stereoscope a white field for one eye and a black field with a white vertical stripe running across it for the other, in the combined fields there will be seen a white stripe bordered by black lines gradually fading off into white. The remainder of the combined field of the black and white will be almost as white as the white stripe. Macdougall [1] explains this as due to the reciprocal re-enforcement of corresponding points with inhibition of adjacent points. The parts of the field which are bright to both eyes predominate over the parts which are bright to one eye only. The parts which are bright to one eye only are partly or completely inhibited. This may also be illustrated by combining a white field with a small black circle in the centre on the other. If the circle be small it appears fully black in the combined field, that is to say the white element in the circle is inhibited. If the circle be made gradually larger a point will soon be reached when only the peripheral parts of the circle will appear black, the centre appearing dull grey; the centre of the circle will appear whiter and whiter as it is increased in size.

[1] *Brain*, 1911, p. 384.

Theories of Binocular Perspective.

Wheatstone's Theory. Wheatstone discovered that two slightly dissimilar pictures, dissimilar in the same way as two retinal pictures of the same object, produced when presented to each eye separately and at the same time a visual effect similar to that of the solid object or objects which were represented. He invented the stereoscope in order to combine these pictures. His theory was that in viewing a solid object two slightly dissimilar pictures were formed on the two retinae and that the mind united or fused them into one.

Brücke's Theory. Brücke declared that there was really no mental fusion of two dissimilar images. His view was that in regarding a solid object the eyes are in incessant and constant motion, and that the observer combines successive portions of the objects and so obtains a perception of binocular perspective. The instantaneous perception of binocular relief is fatal to Brücke's theory.

Le Conte's Theory. "All objects or points of objects, either beyond or nearer than the point of sight, are doubled, but differently—the former homonymously, the latter heteronymously. The double images in the former case are united by less convergence, in the latter case by greater convergence, of the optic axes. Now, the observer knows instinctively and without trial, in any case of double images, whether they will be united by greater or less optic convergence, and therefore never makes a mistake, or attempts to unite by making a

Fig. 13.

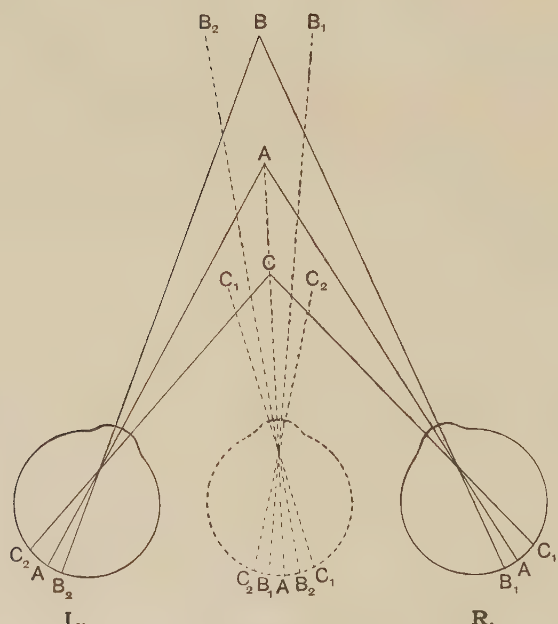


Fig. 14.

Fig. 15.

Fig. 16.

Fig. 17.

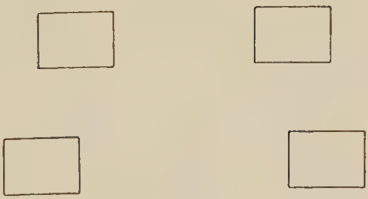


Fig. 19.

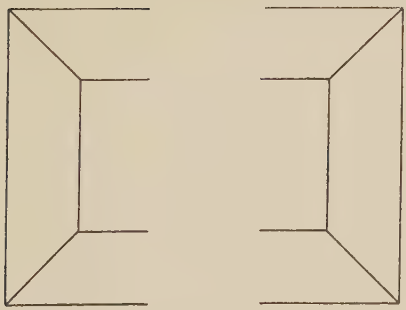


Fig. 18.

wrong movement of the optic axes. In other words, the eye (or the mind) instinctively distinguishes homonymous from heteronymous images, referring the former to objects beyond, and the latter to objects this side of the point of sight."

Le Conte states that this theory is hinted at but not distinctly formulated by Helmholtz.

Hering. Hering holds that retinal disparation is the physiological basis of our ideas of depth, either when the retinal disparation is so small that the images are combined into one or when double images are formed.

My own view is that the perception of relief and binocular perspective is due to the projection outwards of the images falling upon disparate points in association with those falling upon corresponding points to a position in space capable of causing both images. Just as an object is localised monocularly in the visual field so is the appearance of a solid object projected outwards binocularly. When images of two lines fall upon disparate points which are closely together the images are fused and the mind projects outwards the appearance of a solid object which would give rise to the images which are falling upon the retinae. That this is the case is strikingly evident in some stereoscopic pictures. If the stereoscopic pictures of a wire basket which is made up of a number of circles of widely different diameter be examined, we notice that the separate pictures are very different. The small circle which corresponds to the opening of the basket occupies a very different

relative position on the right and left sides. When the picture is examined in the stereoscope a wire basket in high relief is obtained, and it will be noticed that the centre of the circles corresponds from the top to the bottom of the basket. It will be noticed that there is no trace of any double image when the pictures are viewed in the ordinary way, if, however, one portion be intently regarded, the stereoscopic effect will diminish and double images will appear.

It has been stated that when the small circles are combined the large circles are seen double, but though this corresponds to the appearance on the retina it is not what is actually seen.

It will be noted that the combination in many stereoscopic pictures does not take place immediately even when double images are not perceived, then suddenly the figure appears to stand out more and more. On any future occasion the figure is seen at once.

It will be noticed that this view differs from the others in that double images are not essential for binocular perspective. It accounts for the striking perspective which can be obtained with one eye, and the pictures in high relief by combining two halves of a stereoscopic photograph.

CHAPTER XVI.

SUMMARY.

A brief recapitulation may be useful in order to show how the various phenomena of vision can be explained on the theory advanced.

1. Monocular Vision.

The cones are the terminal perceptive visual organs. The rods are not perceptive elements, but are concerned with the formation and distribution of the visual-purple. Vision takes place by stimulation of the cones through the photo-chemical decomposition of the liquid surrounding them, which is sensitised by the visual-purple.

(1) *Visual acuity.*

This corresponds to the distribution of the cones.

(2) *The relation between the foveal and the para-foveal regions.*

There is no qualitative difference between the foveal and para-foveal regions. The Purkinje phenomenon, the variation in optical white equations by a state of light and dark adaptation, the colourless interval for spectral lights of increasing intensity and the varying phases of the after-image have all been found in the fovea only gradually diminished.

(3) *The varying sensibility of the fovea.*

This is explained by the assumption that when there is visual purple in the fovea this is the most sensitive portion of the retina ; when there is none there it is blind.

(4) *Purkinje phenomenon.*

This is a photo-chemical phenomenon and is found with other photo-chemical substances.

(5) *Disappearance of lights falling upon the fovea.*

When the visual-purple in the fovea is used up and not renewed, the latter is blind.

(6) *Currents seen in the field of vision not due to the circulation.*

These are formed by the flow of sensitised liquid.

(7) *Movement of positive after-image.*

This is explained by the shifting of the photo-chemical stimulus.

(8) *Multiple after-images from a single light stimulus.*

These are caused by distribution of the photo-chemical stimuli.

(9) *The Macular Star.*

This corresponds to the canals leading into the external fovea.

(10) *Entopic appearance of cone mosaic.*

This is a subjective appearance of the cones of the retina, the portions occupied by rods appearing as dark spaces.

(11) *The appearance of visual purple between the cones.*

This we should expect on the theory given. The fact is inexplicable on any other view.

(12) *Dark and light adaptation.*

Dark adaptation chiefly due to the accumulation of visual purple in the liquid surrounding the cones, making the liquid more sensitive.

2. Binocular Vision.

In Binocular vision images on the two retinae are combined, the right eye dominating the right side of the field of vision and the left eye the left side. The mind projects outwards the image of an object which would be capable of producing both images, both in the case where different images are formed in the Monocular fields which take part in the combined field and when the images presented to each eye are distinct and there is no object in the combined field which is present in both fields.

CHAPTER XVII.

THE SENSATIONS CAUSED BY SIMPLE AND MIXED LIGHTS.

The physical basis of the simple colours are the colours of the spectrum, and every portion of the spectrum differs in wave-length from that above and below it.

The Limits of the Visible Spectrum.

The limits of the spectrum are practically the lines A and H. A, wave-length, 764 for the red, and H, 396·8. These limits vary with different persons.

Mixed Colours.

All the colours of the spectrum and of nature can be imitated by mixtures of three selected spectral colours, so that in this sense colour vision is undoubtedly trichromatic. It is on this fact that certain methods of colour photography are founded. It does not at all follow, however, that because two simple lights when mixed give rise to the sensation of another simple colour that the receiving apparatus is similarly constituted.

In mixing colours it is necessary to use pure spectral colours. When coloured pigments are used different results are obtained, which are due to the impurity of the light employed. A very good example of the results obtained when using impure colours can be shown with coloured glasses. If we look at a white cloud through a yellow and blue glass combined the cloud appears green, and this corresponds to the mixture of coloured pigments. Every artist knows that when a yellow and a blue pigment are mixed a green is obtained. But this green is obtained by subtraction as is the case with the coloured glasses. If the yellow glass be examined by placing it in front of the slit of a spectroscope, it will be found that in addition to yellow, orange, red and green rays are also transmitted. When the blue glass is examined in a similar manner it will be found that in addition to the blue rays, green, violet and a band of red at the extreme end of the spectrum are transmitted. When the light transmitted by both glasses is examined in a similar manner it will be found that only the green rays are transmitted, and so the colour appears green, which is the only one which can pass through both glasses. When pure lights are used the results are different, and yellow and blue when mixed instead of making green make white.

The following is a table by Helmholtz showing the result of mixing simple spectral colours :

	Violet.	Indigo Blue.	Cyan Blue.	Blue Green.	Green.	Green Yellow.	Yellow.
Red	Purple	Dark rose	Whitish rose	White	Whitish yellow	Gold yellow	Orange
Orange	Dark rose	Whitish rose	White	Whitish yellow	Yellow	Yellow	
Yellow	Whitish rose	White	Whitish green	Whitish green	Green yellow		
Green yellow	White	Whitish green	Whitish green	Green			
Green	Whitish blue	Water blue	Blue green				
Blue green	Water blue	Water blue					
Cyan blue	Indigo blue						

It will be noticed that a mixture of red and blue makes rose, in which a red element is perceptible.

Two colours when mixed which make white are called complementary to each other.

The following is a table of complementaries after Helmholtz :

Colour.	Wave Length.	Complementary Colour.	Wave Length.	Ratio of Wave Lengths.
Red	656·2	Green blue	492·1	1·334
Orange	607·7	Blue	489·7	1·240
Gold yellow	585·3	Blue	485·4	1·206
Gold yellow	573·9	Blue	482·1	1·190
Yellow	567·1	Indigo blue	464·5	1·221
Yellow	564·4	Indigo blue	461·8	1·222
Green yellow	563·6	Violet	433	1·301

It will be noticed that the complementary of green consists of two colours, red and violet, which, when mixed, make the series of purples.

The number of sensations experienced will be considered when dealing with colour perception. The number is very small. Most normal sighted persons say that they see six definite colours in the spectrum, red, orange, green, blue and violet. In addition to these there are the sensations of white and black; white caused by a compound light, and black from the absence of light. It seems hardly fair to include black amongst the sensations, because it corresponds to the silence which is caused by the absence of sound. It is very difficult to obtain a really black object, nearly all reflect a certain amount of white light. The sensation of black is therefore experienced when a very small amount of light falls upon a portion of the retina which is sensitive to light, whilst the adjacent portions are stimulated by a comparatively much larger amount of light.

Colours may differ in three different ways:

(1) Difference of brightness or luminosity.

(2) Difference of hue or colour-tone.

(3) Difference of saturation.

White Light.

When we speak of white light it is necessary to mention the source, as when different sources of white light are examined by the aid of the spectrometer it will be found that their constitution is different. Even when

daylight is employed it must be remembered that its constitution varies at different times of the day.

The term white light used in a physical sense must not be confused with the sensation of white. Blue and yellow when mixed give rise to the sensation of white.

CHAPTER XVIII.

THE SIMPLE CHARACTER OF THE YELLOW SENSATION.

A mixture of two lights may produce an effect which is physiologically indistinguishable from that of a simple light without being reversible, the photochemical substances produced by red and green producing a substance which is similar to that evoked by the simple light, but that the substance produced by the simple light could no more be considered to be constituted of the sensations produced by the components of the compound light than a simple element produced in a non-reversible chemical reaction could be considered to be constituted of the substances which have given rise to it.

It is, however, much more probable that the effects of a mixture of red and green are not actually the same as those of simple yellow, but are physiologically indistinguishable, the retino-cerebral apparatus not being sufficiently developed. The sensation yellow having replaced that of red-green of former ages the two have become indistinguishable. The physical and mathematical aspects of this point of view have been shown

in a very able paper by Houstoun.[1] A corollary to this point of view is that when the colour sense has been still further developed a mixture of red and green will no longer match a simple yellow but will appear as a distinct colour in the same way as a mixture of red and violet make a perfect match with green for the dichromic, but the normal sighted readily distinguish one as green and the other as purple. The following evidence supports the view of the simple character of the yellow sensation:

1. The impossibility of splitting the yellow sensation into its alleged hypothetical constituents when pure spectral yellow is used.

2. That in certain cases of defective colour-perception, pentachromic and tetrachromic, the yellow sensation is diminished and in other cases the trichromic lost altogether, whilst there are three definite colour sensations, red, green, and violet, and the yellow region is seen as red-green.

3. In cases where there is shortening of the red end of the spectrum, and a yellow sensation is present, this yellow sensation corresponds to a portion of the spectrum nearer the violet end of the spectrum than with the normal sighted.

If these cases were caused by diminution of a hypothetical red sensation the opposite should be the case, and the yellow should be found nearer the red end of the spectrum.

4. If the eye be fatigued with pure spectral yellow

[1] *Proceedings of Royal Society*, A, vol. xcii. 1916, p. 424.

light the spectrum will appear to have lost its yellow, and though yellowish-red or yellowish-green will appear less yellow the terminal red of the spectrum will not be affected.

If the terminal portion of the red end of the spectrum be isolated in my spectrometer it will appear as a faint red upon a black background. If the eye be fatigued with red light, even by looking through a red glass held against a light for one second, the red will not be visible for some considerable time, but the eye may be fatigued for twenty minutes with yellow light without interfering with the visibility of the red light.

5. It is known that if the intensity of a number of coloured lights be reduced in the same proportion all the colours do not disappear at the same moment. If, therefore, spectral yellow were a compound sensation it should change colour on being reduced in intensity. If, however, spectral yellow be isolated in my spectrometer, and the intensity be gradually reduced by moving the source of light away, the yellow becomes whiter and whiter until it becomes colourless, but does not change in hue.

6. The eye may be fatigued with red or green without altering the hue of spectral yellow. Spectacles glazed with red or green glass of a kind which is permeable to the yellow rays may be worn for a considerable time without altering the appearance of spectral yellow. If yellow were a compound sensation, a wearer of red spectacles should see the yellow through them as green,

because the yellow would fall on a portion of the retina which had been fatigued for red.

7. In conditions which would appear to be particularly favourable for seeing yellow as red if it were a component sensation this does not occur. If black letters on a white ground be arranged in a dull light so that as little light as possible be reflected from the black letters, and a blue-green glass impervious to the red rays be suddenly interposed between the eye and the letters, the black letters appear for a fraction of a second a brilliant red. If spectral yellow be viewed in similar circumstances it still appears yellow. The explanation of the above phenomenon appears to be that the retina still contains substances caused by the action of white light, and the black letters appear red through simultaneous contrast.

8. Spectral yellow after colour adaptation to green still appears yellow and not red.

9. The after-image of pure spectral yellow is first seen as a bright yellow positive after-image; this does not change to green on becoming negative.

10. The complementary of yellow is never strengthened by the after-image of yellow.

11. The stability of the after-image of spectral yellow is remarkable; it does not change colour and is not influenced by subsequent light falling on the retina when this is not of too great intensity.

12. When the eye is fatigued by red light the after-image projected on yellow is grey or black; no tinge

of colour is seen unless the fatiguing light is very bright, when the yellow image on screen becomes green.

13. When a sodium flame is viewed after fatigue with spectral red light it is very little affected in the region of the after-image, though the green blue after-image is very strongly marked on either side of the sodium flame.

14. A vivid blue-green after-image may be seen not only in the absence of all green light but whilst the eye is still being stimulated by a red light.

15. If yellow were a compound sensation it should be easier to obtain a green after-image after fatigue with red on a yellow than on white. It will be found that whilst the green after-image, is very easy to obtain on a white surface it is much less easy to see on a yellow surface, and much less marked. For this purpose coloured papers are quite satisfactory, because though the colours are not pure the colour indicates the predominating sensation.

The corollary to this view is that those possessing only three colour sensations should see a greater change in yellow than in white, because the yellow region is seen as red-green and does not excite a yellow sensation. This I find to be the case; on examining a trichromic I found that he saw a much greater change in yellow after fatigue to red or green than in white.

16. Bidwell shows that the phenomena of intermittent light are quite inconsistent with the compound character of the yellow sensation. If the image of a white object be suddenly formed on a portion of the retina which

was previously occupied by the image of a black object this image is surrounded by a red border. Bidwell states: "Though the image of the needle was colourless when the patch was illuminated by the greenish-yellow rays of the spectrum, it appeared red when the same hue was formed by combining red and green rays." The fact that the red border is not found with the pure greenish-yellow spectral light and is found with the compound light is strong evidence against the compound nature of the yellow sensation when caused by simple yellow light.

CHAPTER XIX.

METHODS OF EXAMINATION OF THE COLOUR SENSE.

Methods for the examination of the colour sense may be divided into two groups: one of which is chiefly used for scientific purposes, the other when some definite practical object is in view. My colour-perception spectrometer is an example of the first group and the colour-perception lantern of the second.

A. 1. The Colour-Perception Spectrometer.

Description of Apparatus.[1]

This instrument (see Fig. 20) is a spectrometer so arranged as to make it possible to expose to view in the eyepiece the portion of a spectrum between any two desired wave-lengths. It consists of the usual parts of a prism spectroscope, *i.e.* a collimator with adjustable slit, prism, and telescope with eyepiece, of the following dimensions:

Focal length of collimator and telescope object glasses $= 7\frac{1}{8}''$ (180 mm.).

[1] Made by Adam Hilger, Ltd., 75a Camden Road, London, N.W.

Clear aperture of collimator and telescope object glasses $= \frac{7}{8}''$ (22 mm.).

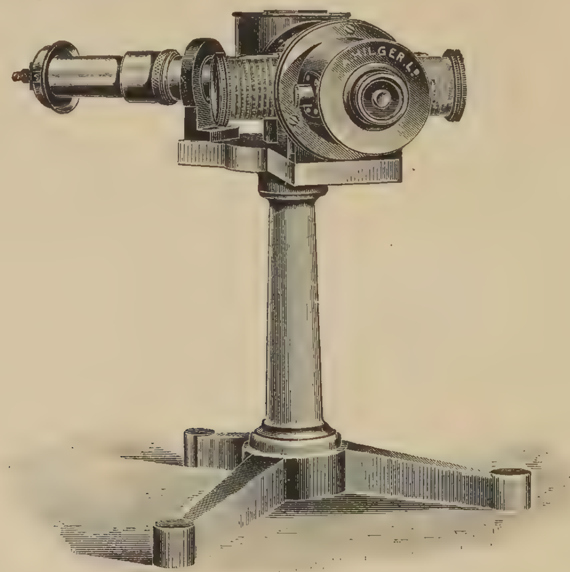


FIG. 20.

Slit, 7 mm. effective length of jaw, with wedge for reducing the effective length of the slit, protective cap, comparison prism, and screw adjustment for the slit width with divided head (see Fig. 21).

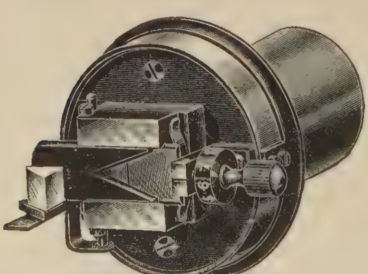


FIG. 21. (0·6 × *actual size.*)

The prism is of flint glass, 1·65 refractive index for D.

Eyepiece, Ramsden form, focussing on to the shutters described below.

In the focal plane of the telescope are two adjustable

shutters with vertical edges; the shutters being carried by levers which rotate about centres near the object glass of the telescope. The shutters can be moved into the field from right and left respectively, each by its own micrometer screw, and to each screw is attached a drum, the one being on the right and the other on the left of the telescope. On each of these drums is cut a helical slot in which runs an index, and the drum is engraved (see Fig. 22) in such a manner that the reading of the index gives the position in the spectrum of the corresponding shutter in wave-lengths direct.

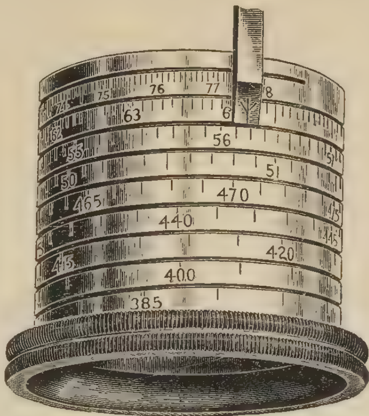


Fig. 22.

Thus it will be seen that if, for instance, the reading on the left drumhead is 5320 and that on the right drumhead is 5950, the region of the spectrum from Wave-length 5320 to Wave-length 5950 is exposed to view in the eyepiece.

An adjustment for the shutters is provided in case of possible zero alterations in course of time. These adjustments (which are provided for each shutter independently) are reached by unscrewing the small screw caps on the right and left of the eyepiece end of the telescope. This exposes a screw with a square head, on to which head fits a key which is provided. To adjust the shutter the corresponding drumhead is set to the

wave-length of one of the sodium lines. The slit is illuminated by a sodium flame, and the key is turned till the edge of the shutter exactly coincides with that line. The key is then removed and the reading checked. The drum will then read correctly throughout the entire spectrum.

Care should of course be taken to avoïd pressing inward with the key, to which only a turning force should be applied.

Directions for Using the Instrument.

The instrument is used as follows: The instrument should be used as far as possible with a known quality and intensity of light. A small oil-lamp is quite suitable for the purpose. The observer should first ascertain the exact position of the termination of the red end of the spectrum, the left-hand shutter being moved across until every trace of red just disappears. The position of the pointer on the left-hand drum is noted, and the wave-length recorded. The left drum is then moved so that the shutter is more towards the middle of the spectrum. The right-hand drum is then moved, until the pointer indicates the wave-length recorded as the termination of the red end of the spectrum. The observer then moves the left-hand shutter in and out until he obtains the largest portion of red, which appears absolutely monochromatic to him, no notice being taken of variations in brightness, but only in hue. The position of the index on the left-hand drum is recorded. The

left-hand shutter is then moved more towards the violet end of the spectrum, the right-hand shutter being placed at the position previously occupied by the left-hand shutter. In this way the whole of the spectrum is traversed until the termination of the violet end of the spectrum is finally ascertained with the right-hand shutter. The variation of the size of the monochromatic divisions and the terminations of the spectrum with different intensities of light can be noted. The instrument is also used for ascertaining the exact position and size of the neutral region in dichromics, the position of greatest luminosity, and the size and extent of pure colours. When it is used to test colour-blindness, the examinee should first be shown some portion of the interior of the spectrum, and then asked to name the various colours which he sees. In this way he will have no clue to the colours which are being shown him.

2. Mixing Spectral Colours.

This method gives very valuable information on certain points, but it is totally wrong to assume, because two colours when mixed give rise to a sensation of a simple colour, that our colour-sensations are similarly constituted, especially when there is direct evidence that such is not the case. A really efficient colour-mixing apparatus is greatly to be desired. There is no really efficient colour-mixing apparatus in existence combined with such simplicity of construction as will enable it to be used without taking too long over the

procedure. This is the great objection to the large instruments of Helmholtz and Hering.

Colour-mixing apparatus in which the spectrum is projected upon a screen are not suitable when great accuracy is required, and have been generally abandoned on the continent.

The chief desiderata in an instrument for mixing spectral colours are as follows :

1. The instrument should have a wide dispersion, so that the colours should be as free as possible from light of adjacent wave-lengths.

2. Each single colour should appear monochromatic when viewed by a person with acute colour perception.

3. Each colour should be as free as possible from admixture of white light or light of other wave-lengths.

4. The light used should not be so intense as to produce after images or perceptible fatigue.

5. The mixed colours should combine completely in the eye of the observer.

6. The colours to be compared should just touch, but not overlap.

Very valuable information may be obtained by mixing pure spectral colours. It can be seen how far the colours of the simple spectrum may be matched by mixtures of other colours. When these experiments are being made it is absolutely necessary to use colour-names, just as in every other method of examining the colour-sense. For instance, when a simple yellow is being matched by a mixture of red and green the

examinee should be asked to name the simple colour, and then told to match it with a yellow of similar hue and luminosity. In this way he will be prevented from making a match which corresponds in luminosity and not in hue. Lithium red and thallium green ($\lambda 670 + \lambda 535 = \lambda 589$) when mixed make a yellow which is similar in colour to sodium yellow. Whilst the majority use certain proportions of red and green, others are anomalous, some requiring more red and others requiring more green in the mixed colour. Those who require more red are called red anomalies, and those who require more green, green anomalies.

Lord Rayleigh's instrument gives the best results, and the match is an exact one. Several modifications of his instrument have been constructed but they are defective. For instance, in the instrument of Nagel, the proportions of the lights in the mixed colour are regulated by two slits, one of which is enlarged whilst the other becomes smaller. It is obvious that when one slit is increased in size the colour becomes less pure, being mixed with light of adjacent wave-lengths. This is not a satisfactory method of regulating the intensities of the two lights. The following is a summary of the information which may be obtained by mixing spectral colours :

1. The various proportions of different colours which when mixed match various simple colours in the spectrum.

2. The wave-lengths of complementary colours, and the variation with different persons.

3. The exact proportions of the complementary colours which are required to make white light with different persons.

4. The varying proportions of red light taken from different regions which will make white with a given blue-green.

5. The different proportions of violet light taken from different regions which will make white with a definite greenish-yellow with different persons.

6. The different proportions of three definite colours which when mixed will make white light with different persons.

7. The different proportions of red and violet which when mixed will match the neutral region in different dichromics.

3. General Classification of Colours.

In this method my classification test may be used. I have given full directions for the use of this test.[1] This method confirms in the strongest manner the examination with the spectrometer. The colour-blind will classify in accordance with their colour-perception. It is necessary to use coloured objects of different materials in order to force the examinee to use his colour perception in classifying them. Most dichromics will not put a green and a yellow wool together, because the latter appears so much brighter, but they will put a green silk skein with a yellow wool skein, and they will put red,

[1] *Hunterian Lectures on Colour Blindness and Colour Vision*, p. 66.

green and yellow glass with both. Only a few of the differently coloured materials should be given at a time, so that they may be matched with the wools and not amongst themselves. The colours used should represent the whole series of colours, red, orange, yellow, yellow-green, green, blue-green, blue, violet, purple, crimson, and numerous shades of brown and grey. The classification should be made entirely under definite colour-names, as, for instance, red, yellow, green and blue.

4. The Bead Test.

The test consists of a number of coloured beads in which every variety of confusion colour of the colour blind is well represented and a box with four compartments into which the beads can be dropped. The aperture to each of the compartments is such that the observer cannot see the bead after it has been dropped into the box. The four compartments of the box are labelled red, yellow, green and blue.

Directions for conducting the test. The examinee is told to pick out from the beads in front of him, all those that are red, keeping as nearly as possible to the exact hue but selecting those that are lighter or darker of the same colour, and to drop them one by one into the compartment labelled red. He then goes through the same process with the three other colours; he is not allowed to compare the colours directly but must select them entirely according to the name which he

gives to the colour. It will be found that whilst the normal sighted are able to select the correct colours with the greatest ease, the colour blind will make their characteristic mistakes. This test like the lantern will detect cases of colour scotoma as well as those of ordinary colour blindness.

5. Card Test.[1]

Preliminary Remarks.

This test is, perhaps, the simplest for demonstrating to the normal sighted person defective colour vision in a subject.

The principle involved is the perception of difference between two colours presented in a special diagram of spots of irregular shape and various tones. On a ground of separate spots of one colour a letter is formed in spots of another colour. The test consists in discriminating between the colours, and hence recognising the letters.

New Features of the Test.

The new features of this test are: (*a*) The construction of a special diagram so arranged that there is no indication by way of form or tone, given of any letter which is formed upon it. It will be seen that the diagram, *i.e.* the shape, relative position, and number of the spots is the same on all twenty-two cards, *the only method of distinguishing the spots which form the letter being a*

[1] Published by G. Bell & Sons, Ltd.

difference of colour from the other spots. The examinee is forced to judge by colour perception alone.

(*b*) On a given card the colours exhibited are those which appear to be the same colour to the particular class of colour blind which that card is designed to detect, each card having a special purpose. The colours correspond to portions of the spectrum which, when isolated, appear all of a uniform colour to a class of colour blind.

(*c*) There are special cards for the detection of cases of shortening of the spectrum both at the red and the violet end, *i.e.* to detect inability to distinguish certain reds or violets from black, and also special cards to detect shortening of the spectrum combined with defective colour differentiation.

Instructions in the Use of the Test.

The cards should be presented in good daylight and at a distance of about two feet, the order of presentation being varied in testing different persons. A card should be selected (No. 1, for instance), and the examinee asked to name the colours on the card. When he has done so he should be asked to point out with his finger or a small pointer all the spots of that particular colour (named by the examiner) of which the letter is built up. When he has done this, it should be pointed out to him that these spots form a letter (M in the case of No. 1), and it should be explained that on all the other cards a letter is exhibited in a similar way, by colour difference. If the examinee fail to distinguish any colour difference on the

first card shown, others should be shown to him successively until one is found with which he is successful. If he be unsuccessful with all the cards, the examinee is to be set down as dichromic, *i.e.* only able to distinguish two colours, red and violet, which he will be able to name on different cards. These two colours, *pure* red and violet (crimson is not a pure red), are not presented together on one card, so he will fail to distinguish a letter on all the cards.

According to the cards with which the examinee is successful his degree of colour-vision can be judged by considering the following particulars as to the cards :

No. 1. *Crimson and Blue.* Failure to read this card indicates shortening of the red end of the spectrum.

No. 2. *Olive-Green and Red.* Failure to read this card indicates that the examinee is dichromic. Trichromics will find it difficult, but will probably succeed ultimately.

No. 3. *Orange and Yellow-Green.* This cannot be read by dichromics or trichromics.

No. 24. *The Whole Range of Colours Used.* This card shows the whole range in squares of colour. The examinee is asked to name the colour of all the squares. It is not to be expected that he will name them all correctly as in the list in the next paragraph, but he should name them correctly, as red, green, blue, or yellow. If myrtle-green be called green it will be sufficient, but if it be called red it will indicate colour blindness. While failure with this card is conclusive proof of

colour blindness, it is not easy to conclude the degree of colour blindness, and success with this card is not a proof of perfect colour vision. The card is a rough general test, but it is in no way conclusive except in the gross cases. The other cards constitute the final test.

5. Range of Colours.

List of Colour Tones used on the Squares of Colour Chart Numbered in Order reading from Left to Right.

1. Myrtle-green	Light.	2. Green	Medium.
3. Purple	Medium.	4. Green	Light.
5. Blue	Light.	6. Orange-brown	Light.
7. Grey	Dark.	8. Olive-green	Medium.
9. Orange	Light.	10. Crimson	Medium.
11. Yellow-green	Light.	12. Violet	Light.
13. Myrtle-green	Dark.	14. Olive-green	Light.
15. Red	Light.	16. Violet	Medium.
17. Blue-green	Medium.	18. Yellow	-
19. Red	Medium.	20. Purple	Dark.
21. Crimson	Light.	22. Blue	Dark.
23. Orange-brown	Medium.	24. Yellow-green	Medium.
25. Orange-brown	Dark.	26. Green	Dark.
27. Orange	Medium.	28. Brown	Dark.
29. Blue-green	Light.	30. Grey	Medium.
31. Myrtle-green	Medium.	32. Olive-green	Dark.
33. Purple	Light.	34. Blue	Medium.
35. Crimson	Dark.	36. Brown	Medium.
37. Orange	Dark.	38. Violet	Dark.
39. Blue-green	Dark.	40. Red	Dark.
41. Grey	Light.	42. Yellow-green	Dark.

The complete test consists of 24 cards, 22 of which are similar in character to Nos. 1, 2, and 3. No. 23

consists of circular spots of colour of varying size similar to No. 24 in the test.

6. Painting Pictures.

This method is a very useful one for obtaining information of the mistakes made of the colour-blind. I use a variety of the small pictures which are employed for teaching children painting. These pictures consist of a copy which is coloured, together with a pencilled outline in which it is only necessary to fill in the colour. A large number of colours should be arranged on plates, both primary and mixed, so that the examinee may have as little mixing as possible to do himself. I have a large series of paintings made in this way, and a selection of these may be found in my book.[1] I have had a number of these pictures made into lantern slides, and whenever I exhibit them I am certain to be asked by someone in the audience why it is the characteristic mistakes are made and why the right colour is not more often used. The reason of this is the colour-blind do not guess in a haphazard way, but paint the pictures in accordance with their colour-perception. When two colours are twin colours, that is to say, two colours appearing in every respect identical, as, for instance, a pink and a blue or a red and a green, then it is more or less chance as to which colour is selected. Both colours will be represented by the same colour, for instance, if a colour-blind decide that a certain pink is blue, he will pick out

[1] *Colour-Blindness and Colour-Perception*, International Scientific Series.

a blue to paint it with, but if he select a pink he will almost certainly represent blues with the same pink. A trichromic on looking at the copy will notice that a yellow adjacent to a red appears green, and will represent it by green, or a yellow adjacent to a green appears red, and will accordingly represent it by red. Experience in painting and minute comparison will undoubtedly eliminate many of these errors, especially when the artist is assisted by a normal-sighted person. For instance, the colour-blind artist may learn that yellow placed adjacent to red appears green whilst it remains practically unaltered to a normal-sighted person. He would then represent yellow adjacent to the red by yellow, knowing that the latter colour would change when placed adjacent to the red; this, however, is not at all likely to occur without considerable previous experience.

In ordinary circumstances, however, just as in naming colours, the examinee will pick out the colours which represent different colour sensations to him. A trichromic, for instance, whose colour sensations are red, green, and violet, will try to represent all colours by these three. In fact, pictures of this kind are quite common in public picture galleries.

Faint washes of colour may be used also as a test, the examinee being asked to name them.

B. The Colour Perception Lantern.

The special use of this lantern is for examining candidates for admission into the Navy and railway services.

The conditions in which the lights are actually seen are imitated. I have given full details of its construction and use.[1]

The lantern[2] is made in several forms, each of which is efficient. In the latest form the apertures are on one of the discs. See Fig. 23 for latest form.

Various distances can be represented in accordance with the requirements by varying the distance of the observer from the lantern. When space is limited the correct distance can be imitated with the aid of plane or convex mirrors.

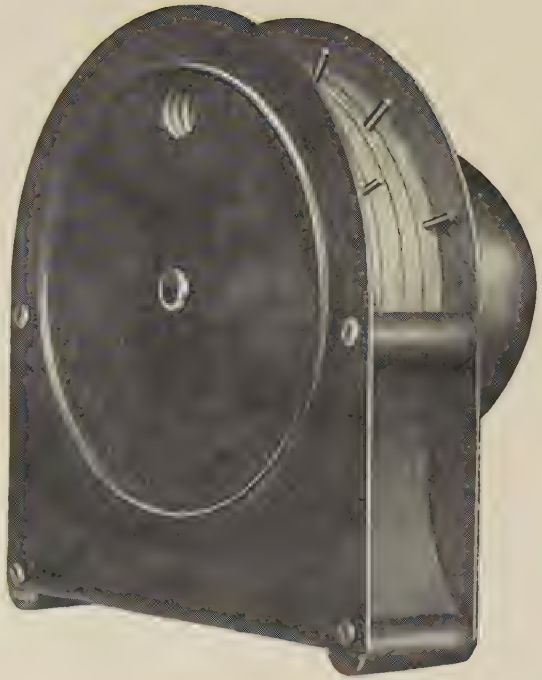
Directions for Use.

Construction. The lantern consists of four discs: three carrying seven coloured glasses and one carrying seven modifying glasses. Each disc has a clear aperture. The other mechanical details are: an electric or oil lamp with projecting accessories, a diaphragm for diminishing the size of the light projected, handles for moving the discs, and the indicator showing the colour or modifier in use.

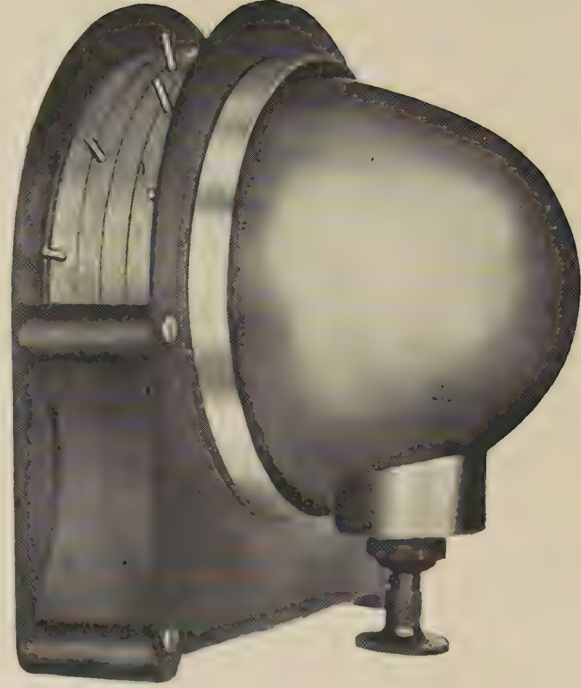
Diaphragm. This is graduated in respect to three apertures to represent a $5\frac{1}{2}$ inch railway signal bull's-eye at 600, 800, and 1000 yards respectively when the test is made at 20 feet.

[1] Made by Rayner & Keeler, 9 Vere Street, W.

[2] *Colour-Blindness and Colour-Perception*, International Scientific Series, Kegan, Paul, and Co., and *Hunterian Lectures on Colour-Vision and Colour-Blindness*, Kegan, Paul and Co.



Front View.



Back View.

Fig. 23. THE EDRIDGE-GREEN COLOUR PERCEPTION LANTERN.

Face page 162.

Colours. Three of the discs contain :

1. Clear	5. Green.
2. Red A.	6. Signal Green.
3. Red B.	7. Blue.
4. Yellow.	8. Purple.

One disc contains the following modifying glasses :

Clear.	Neutral 2.
Ground Glass.	Neutral 3.
Ribbed Glass.	Neutral 4.
Neutral 1.	Neutral 5.

Method of Using. The colours are brought successively into view by moving one or more of the handles to position, denoting the colour or modifier in use, on the scale at the top of the lantern.

Notes on Testing. Show each colour in one disc, and the modifying glasses in combination, and *obtain a name* for each, occasionally asking the candidate to match the lights with coloured wools, silks, cards, etc.

Colour ignorance demands rejection, but the candidate may be re-examined.

The candidate should be seated at a distance of 20 feet from the lantern. He should be asked to name the colour of the light produced by a coloured glass alone or in combination with the modifying glasses or the coloured glasses. A candidate should be rejected (I.) If he call the red, green, or the green, red, in any circumstances. (II.) If he call the white light in any circumstances red or green, or *vice versa.* (III.) If he call the red, green, or white lights, black, in any circumstances.

A candidate who makes mistakes other than those mentioned above should be put through a very searching examination.

The examiner should on no account conduct the examination on any regular plan, because the candidate, anxious to pass, finds out from persons who have already passed, the order and method of the examination ; and so though colour blind might obtain a certificate. Any one of the glasses may be shown first, and the candidate required to name the colour of the light. The following will serve as an example of the method to be employed in testing a candidate. A red being shown, the candidate is required to name its colour. Then a blue or green may be substituted, then one of the neutral, ground, or ribbed glasses ; not the slightest intimation being given to the candidate of the nature of the colour. He should be asked to name or describe the light, and the answer, if correct, together with his other replies, carefully recorded. The other glasses may then be shown, a combination of the neutral, ground, ribbed and coloured glasses being used at intervals. Twenty correct answers may be considered sufficient for a pass certificate.

One incorrect answer to any of the questions under test A suffices for rejection. The examinee giving a doubtful answer to any of the questions in tests B, C, and D should be subjected to a very searching examination. The procedure should be varied in every case. Questions with doubtful answers should be repeated

after an interval of other questions. Answers should on no account be commented upon.

Summary of Method of Examination. (1) Show all the colours on one disc with the largest aperture. (2) Show the reds, greens, and yellow modified by the neutral glasses. (3) Show all the colours on one disc with Number 3 aperture. (4) Show red, then immediately afterwards yellow with largest aperture. Then show green and yellow immediately afterwards. (5) Test the candidate with the red, green, and yellow with the smallest aperture. (6) Show the neutrals or ground glass alone. (7) Show blue made by combining blue or purple with the signal green. (8) Show a colour, for instance, green, and then combine another glass of the same colour. (9) Show the red produced by the combination of purple with red A. (10) Give a combination of red A and signal green.

A form of questions with answers, making a series of hypothetical cases with results, are given in the table on page 166.

If all questions be correctly answered a more searching test can be made by using the smallest aperture and requestioning.

C. Peripheral Colour-Vision.

A perimeter in which spectral colours are employed is greatly to be desired. A perimeter in which coloured papers or pigments are used is of very little scientific value on account of the composite character of the light

reflected from the coloured surfaces. When spectral colours are employed entirely different results are obtained

Question.	Answer.	Result.
TEST A.		
1. Red A or B - -	Green - - -	Reject (Dich.).
2. Green - - -	Red - - -	Reject.
3. Clear - - -	Red or Green -	Reject.
4. Red, Green, or Clear	Black - - -	Reject.
5. Yellow - - -	Green - - -	Reject.
6. Yellow - - -	Reddish Green -	Reject (Tri.).
7. Neutral 4 - -	Green - - -	Reject.
TEST B.		
1. Green with neutral 4	Red - - -	Reject.
2. Red A or Red B with neutral 4 - -	Black - - -	Reject (shortened red).
	Green - - -	Reject.
3. Red A with Purple -	Black or Green -	Reject.
TEST C.		
1. (*a*) Yellow - -	Doubtful - -	Reject (Tri.), particularly if Green or Red be positively stated at (*c*) and (*e*).
(*b*) change to Red -	Red - - -	
(*c*) change to Yellow	Green - - -	
(*d*) change to Green	Green - - -	
(*e*) return to Yellow	Red - - -	
2. (*a*) Red A or Red B with neutral 4	Green - - -	Reject (Di.) for (*a*) and (*c*).
(*b*) remove neutral 4	Red (doubtful) -	
(*c*) replace neutral 4	Green - - -	
TEST D.		
1. Blues - - -	Green - - -	Reconsider.
2. Yellow - - -	Red - - -	Reconsider.

to those with pigmentary colours. Landolt stated that when spectral colours were employed of sufficient size

and intensity these could be seen as their correct colour to the extreme periphery. This is certainly the case with spectral red light. I find that spectral red can be seen of precisely the same quality red to the extreme periphery of the field of vision. I can find no colourless interval at all when the light used is sufficiently bright. I have tested a number of persons with the same result; the statement therefore that the peripheral regions of the retina are totally colour blind is an error. Gotch has made a number of experiments with small spectral lights with a dark adapted eye and finds that the colour field for red is much larger than that for green, but whilst red is only seen as feeble white from a small distance outside this colour-field, green is seen as a bright white light for a considerable distance.

Those with defective colour discrimination have correspondingly restricted fields of colours. As colour blindness of the periphery is only relative the exact point at which it is necessary to raise the luminosity of spectral lights of different wave-lengths before colour is seen can be ascertained by making comparison at the same time with a white light the luminosity of which can be varied. It will be seen then that at one luminosity both the coloured light and the white light appear as white and can be matched, but on increasing the luminosity of both in the same proportion a point is reached when the coloured light appears as coloured.

CHAPTER XX.

HEXACHROMIC VISION.

The hexachromic are those who see six definite colours in the spectrum and have six definite colour sensations. They describe the spectrum as consisting of red, orange, yellow, green, blue and violet, and state that all the other colours in the spectrum are plainly modifications of these six and can be correctly described by a combination of two of the names which are applied to the fundamental sensations. For instance, both the yellow and green characters are plainly visible in yellow-green. If we examine the colours to be found in nature we shall see that all the colours may be classified under one or two of these fundamental sensations. Most normal-sighted persons would readily agree that red, yellow, green and blue are fundamental sensations, but some would demur as to orange and violet being considered as such. The reason of this is two-fold, the first is that very few of the violets to be met with in nature are true violet, nearly all contain a red element. In order, therefore, to see a true violet the colour must be examined through a piece of blue-green glass, which is impervious to the red rays. Its characteristic

and cold appearance is then evident. The second difficulty is that of getting rid of the bias due to the knowledge of mixing colours. If we look at any shade of orange from the lightest to the darkest we shall find it is a definite colour and has received a definite colour name. Orange being on my view the last colour sensation to be developed is undoubtedly the weakest colour, but to me orange is most definitely a fundamental sensation. I cannot see any trace of either red corresponding to the ruby glass or yellow in a pure orange. I am quite unable to analyze orange into red and yellow and the term reddish-yellow does not describe orange to me.

We should expect that if colours were developed in a certain order a certain intensity of light would be necessary for their recognition and that the last developed colour would require the most favourable circumstances for its recognition. We should expect, therefore, that if the intensity of the spectrum were gradually diminished the colours would disappear one by one in the reverse order of the development, and that we should pass through all the stages of defective colour perception, until at a certain intensity the spectrum became colourless. This we find to be the case, first the orange disappears and the spectrum has only five colours, on still further diminishing the intensity, the spectrum appears as first four, and then three colours, red, green and violet and is trichromic in character. The results of further diminution depends upon the relative intensities

of the components of the light used. Finally the whole spectrum appears colourless.

The interval which intervenes before coloured light is seen as coloured on gradually increasing the intensity is called the photo-chromatic interval. This is smallest with red light. A different result is obtained when a small portion of the spectrum is isolated in my spectrometer and the intensity of the light gradually reduced by moving it on a scale away from the spectrometer. There is no change in tone in pure yellow or pure blue as the intensity is diminished: both appear darker and whiter until they finally appear colourless.

Burch[1] states that when the eye is sufficiently dark adapted, there is no photo-chromatic interval and a light which previously appeared colourless appears coloured. I have often after having obtained a colourless spectrum seen the orange reappear as red after ten minutes dark adaptation.

When I reduce the intensity of the spectrum in my spectrometer in a room which is not completely dark, the last portion of spectrum to present an appearance of colour is the region of orange red, which appears reddish-white, the blue and violet appear white as well as the green. The red is invisible up to the point mentioned. As the eye becomes dark adapted so does it increase its sensitiveness to violet, and the blue-violet now appears as violet. All this is in accordance with our general experience. If we are taking a walk

[1] *Proc. Royal Soc.*, B. 76, 1905, p. 213.

at sunrise it will be noticed that red objects appear black, whilst orange objects appear reddish-white and the blue of the sky is plainly visible. The first colours to be recognised are the oranges which appear reddish-white and the blue which appears violet, green objects appear grey. As the light increases green objects can be seen, then yellow, then blue and lastly orange in its true colour.

It will be seen, therefore, that the hexachromic have six definite colour sensations, each of which requires a certain intensity of light for its stimulation. The red and green light both excite the yellow sensation, but yellow light does not excite the red and green sensations ; in the same way both violet and green light which is on the blue side of the centre of the green excite the blue sensation. But blue light does not excite either the green or violet sensations.

The explanation of complementary colours is a component part of my theory of colour vision. In the dichromic any colour on one side of the neutral region is complementary to any other on the other side of the neutral region. When the evolution of the colour sense has reached a point at which a mixture of red and violet no longer cancel each other and appear white, but give rise to a distinct sensation, and simple green light also gives rise to a distinct sensation, the apparently trichromatic nature of colour vision has been reached. Any three primary sensations or any two secondary sensations representing the whole of the spectrum cancel

each other and leave the original white sensation. This white sensation should have and does have the total luminosity of its components.

The same explanation may be given to the formation of yellow by a mixture of Lithium red and Thallium green. In this case only half of the spectrum is represented and so the mixture appears yellow, the red and green elements having cancelled each other. It should be noted that the match is an exact one, both in hue, luminosity and saturation. The mixed colour is not, as is often stated, less saturated than the simple one, both the simple and the mixed colours appear to be identical physiologically. I have been unable either by colour fatigue to red or green, colour adaptation or dark adaptation to distinguish between the two.

CHAPTER XXI.

HEPTACHROMIC VISION.

There are individuals who are able to distinguish differences of colour, which are not perceptible to the hexachromic. Just as the hexachromic are dissatisfied with the monochromatic divisions marked out by those with a lower degree of colour perception, so do the heptachromic object to the marking out of the hexachromic. Twenty-nine is the largest number that I have had marked out by any person. The heptachromic declare that they see seven definite colours in the spectrum. The seventh colour is in the region of the blue-violet. They agree, therefore, with Newton that there are seven colours in the spectrum. The heptachromic appear to have a much better colour perception than the hexachromic in every way. They will work for a considerable time with colours without becoming tired, and they can match colours by memory with much greater ease. I have let a heptachromic isolate a region of the spectrum in the blue-violet and then next day asked him to isolate the same region and found that he has been able to do this correctly and between the same wave-lengths.

Houstoun[1] has written a very interesting paper on heptachromic vision. He comes to the conclusion that Newton was a doubtful heptachromic, but that his assistant was a true heptachromic. Houstoun has met with several cases. It will be necessary for a large number of persons to be examined in similar conditions with a spectrometer before the percentage of heptachromics in the community and other degrees of colour discrimination is correctly known. Houstoun has done this with seventy-nine observers.[2]

It might be thought that a number of divisions in the spectrum and the number of colours seen might depend upon the accuracy of observation of the observer and not his colour perception, but this is not the case. One of the heptachromics examined by me was a mechanic with no knowledge of colour vision. He was pointed out to me as colour blind because he persisted in calling a colour blue which his fellow workmen all agreed in calling a violet. When examined with the spectrometer he stated that there was a dark blue visible between the blue and the violet though no other observer could see any colour there, neither was the spectrum particularly dark. The heptachromic see more yellow in the spectrum and also an orange of a larger size than a hexachromic. An interesting point is that when the blue and the dark blue of the heptachromic are marked

[1] R. A. Houstoun, *Newton and the Colours of the Spectrum*, *Science Progress*, vol. xlvi., p. 250, 1917.

[2] *Proc. of the Royal Society*, A, vol. xciv., 1918, p. 576.

out the dark blue is much larger in area than the blue. If, however, each of these colours be bisected and the centres joined we now find that we have marked out the blue of the hexachromic. It is probable, therefore, that there is some simple mathematical relation between the two classes and between all classes of colour discrimination. It will be noticed that the blue of the heptachromic encroaches on the green of the hexachromic.

A heptachromic therefore calls a colour blue which a hexachromic calls green; this is just the opposite to the mistakes of the pentachromic, who include a portion of blue in their green.

I have also used squares painted with various mixtures of colours which were not perceptible to the hexachromic and have had them readily discriminated by the heptachromic.

The term indigo which was used by Newton for the seventh colour of the spectrum is not a good one, because the ordinary indigo paint which is used by artists is a greenish blue and not a violet blue.

CHAPTER XXII.

COLOUR BLINDNESS.

Cases of colour blindness may be divided into three distinct classes each of which may occur separately or they may be combined. These classes are (1) Defective hue discrimination. (2) Defective light perception. (3) Defective perception of colour through the foveal or central region of the retina not being normal, or supplied normally.

(1.) Defective Hue Discrimination.

Our colour perception is much more limited than is usually stated. If a pure spectrum be examined in my spectrometer, in which any portion of the spectrum may be isolated between any two desired wave-lengths, most normal sighted people will divide the spectrum into about eighteen divisions each of which appears absolutely monochromatic though we know it contains a large number of rays of different wave lengths. These monochromatic divisions may be considered the units of the discrimination of colour. If they be examined by means of a double-image prism so that two images of the division may be seen, or they may be projected with the

aid of a double-image prism upon a screen, still no difference is seen in the components of the division even with the aid of simultaneous contrast. It will be noticed that in this method of observing the region, the red side of one image is made to touch the violet side of the other. In this experiment care must be taken that the luminosity of both images is similar, for if the intensity of one be greater than the other a difference will be immediately noticed. The same will occur if one image be mixed with light of other wave-lengths. Neglect of these precautions has made other observers believe that they could discriminate between colours occupying a relatively closer position in the spectrum.

The largest number of divisions which I have found made by one person has been twenty-nine and I have examined cases which extend from this number to those who could only see the spectrum as colourless varying in luminosity in its different parts.

There is another method of using the spectrometer and that is in order to find out the number of colour sensations possessed by different persons. If a bright spectrum be projected upon a screen and a number of men be asked to indicate with a pointer on the screen the number of colours which they see it will be found that there will be a considerable variation in the replies which are received. Each one is asked to show where the spectrum commences and ends, the boundaries of the colours which appear as definite and primary colours to him, and the part which appears brightest. At

present we are only concerned with the number of colours which are seen in the spectrum. One man will declare that there is no difference in colour over the whole spectrum but simply variations in brightness, another will say that the spectrum is tinged with red at one end and violet at the other, the central portion of the spectrum being colourless; another that the spectrum consists of two colours, red and violet, with a small colourless interval; another that the spectrum contains three colours, namely: red, green, and violet, the orange and yellow regions being designated red-green and the blue region green-violet. Another will say that he sees four definite colours, others five or six and a few seven. It will be seen that our colour sensations are very limited, the person having the most acute colour perception only having seven definite colour sensations. We can, therefore, classify the colour perception of individuals as achromic, dichromic, trichromic, tetrachromic, pentachromic, hexachromic, and heptachromic.

The term "dichromic" is applied to those who have only two definite colour sensations and white. When examined with a bright spectrum they say that they see only two colours there. In the same way the designations trichromic, tetrachromic, pentachromic, hexachromic, and heptachromic, are applied to those who see in the bright spectrum three, four, five, six or seven colours. Those examined behave in every way as if they possessed the number of colour sensations indicated.

This classification is to a certain extent arbitrary, because the degree of brightness of the spectrum requires to be defined and the degrees of colour perception run imperceptibly into each other. The classification is made with a spectrum of such intensity that the six main colours of the normal-sighted are plainly visible, red, orange, yellow, green, blue, and violet. It is obvious that a man who in these circumstances describes the spectrum as consisting of only two or three colours does not see the spectrum like the majority of the normal-sighted.

Achromic Vision.

Many congenital cases of this condition have been described. When there is any colour perception at all the extremes of the spectrum are distinguished. I have examined a signalman who became totally colour blind from an attack of tetanus; his visual acuity was quite normal. His perception of luminosity did not appear to be affected.

Dichromic Vision.

It must not be concluded that a man who stated that there were more colours in the spectrum than two was necessarily not dichromic. It will be seen from the cases I have given that many dichromics have applied different colour names to the various divisions of the spectrum. This only occurs when the examinee has some idea of the region presented to him. The presence

of a neutral area, the confusion of red, yellow, and green with each other and purple with green and grey are diagnostic of the dichromic. The trichromic see three definite colours in the spectrum, red, green, and violet and say that the spectrum is red, red-green, green, green-violet, and violet; they have no neutral point; they mark out a greater number of monochromatic regions than the dichromic; they only in conditions of special difficulty confuse red and green and they see purple as a definite colour and do not in ordinary circumstances confuse it with grey and green.

All authorities are agreed that the cases which I have designated dichromic have dichromic vision, but there is considerable difference of opinion on most of the essential details and as to the nature of the defect.

It should be noted that the term dichromic is used in the above sense and not in that of colour mixing. It is totally wrong to assume because two colours present a certain appearance when mixed that our colour sensations are similarly constituted. All the cases described here as dichromic also appear as dichromic on colour mixing methods, that is to say, all colours may be matched by proportional mixtures of two selected spectral colours taken from the two ends of the spectrum and white. There are, however, borderline cases in which the observer will see three definite colours in the spectrum red, green, and violet when this is bright, but only two when it is of low luminosity. He will be dichromic in all conditions of difficulty in colour discrimination as

with feeble unsaturated colours occupying a small visual angle.

In favourable conditions as with luminous colours of full saturation occupying a large surface he will be trichromic. In a case of this kind a dichromic colour match which is good for a small area is not true for a large area of precisely the same colours, a distinct colour difference is then seen.

All Dichromics are not equally Colour Blind.

A fact that seems to have been generally overlooked is that colour blindness found in dichromic vision is a defect of hue perception, and that it is this defect of hue perception which causes the characteristic symptoms of colour blindness.

The colour perception of the dichromic varies from those who have a colour perception bordering on the trichromic to those who are almost totally colour blind. It is obvious that a man who cannot see the least difference between the colour of the red and that of the green signal on the railway line, except when one is changed to the other, has a colour perception which is more defective than that of the ordinary dichromic. Though I have never found a dichromic who had a hue perception equal to that of the trichromic, I have examined many who possessed a hue perception which was nearly equal.

It is on account of the hue perception possessed by dichromics varying that their detection by some tests is so uncertain. One dichromic will pass all but the most

stringent tests, whilst another will fail with a very inefficient test.

The fact that one dichromic makes so many mistakes that he is readily detected by his acquaintances and another may become a Royal Academician without his colour defect being suspected illustrates the difference in hue perception which is found with dichromics. I have examined some of the pictures painted by a dichromic Royal Academician and was quite unable to detect any defect. This showed how accurately he was able to match. His daughter told me that her mother used to give him the correct colours. An artist was sent to me lately because the head of the academy at which he was studying said he was painting his pictures too coldly and he thought there must be some slight defect of colour perception. On examination I found that he was a dichromic with slight shortening of the red end of the spectrum. He saw two colours, red and violet, in the bright spectrum. He brought a number of his pictures for me to examine and the only fault which appeared specially noticeable was that the pictures were too cold. They did not appear to have enough red in them. This artist had passed through his artistic career without suspecting that he was colour blind or any of his fellow students suspecting it, whilst they detected a slight defect of light perception which is common in those who have hexachromic vision. He was intensely surprised when I told him that he only saw two colours instead of the normal six. This illus-

trates the point that those possessing a defect of light perception or some other defect are much more readily detected than those who have uncomplicated dichromic vision bordering on the trichromic. If a number of dichromics be examined with my spectrometer all will say that they see only two colours in the spectrum, but they vary very considerably as to the size of the portion of the spectrum which, when isolated, appears monochromatic; one dichromic will declare that he sees only two colours in the spectrum and each of these colours is quite uniform, but differs only in luminosity; another will say that the whole of one colour is monochromatic until the neutral point is nearly reached, that is to say, he sees several differences of colour in the neighbourhood of the neutral region.

It will be noticed, therefore, that dichromics vary as to the position at which they see an element of their second colour coming in; those dichromics who are bordering on the trichromics usually see about eight distinct differences in the spectrum, that is to say, one sensation appears to considerably over-lap the other; green for instance is designated as a much less saturated colour than red; a man of this kind will see a very definite difference between red, yellow, and green, and therefore be able to match very accurately when only the primary colours are taken.

One of my dichromics for instance holds the record for matching Sodium yellow with a mixture of Thallium green and Lithium red. He made the ordinary normal

match, but in making a number of observations he had less mean deviation than any other person I have examined, normal sighted or otherwise.

The following are a series of cases examined with my spectrometer, they are not selected cases but all the cases examined by me during a short period and in precisely similar conditions. The eye was light adapted, the illumination 180 meter-candles, the size of the slit was the same and the kerosene used was taken from the same supply. The spectrometer was also kept unmoved during the whole of the period.

No.	Beginning of the Red.	End of the Violet.	Middle of Region of greatest luminosity.	Middle of Neutral Region.
1.	724	436	610	509·5
2.	780	409	573	498·3
3.	775	416	619·5	509·5
4.	680	420	566	493
5.	780	395	—	500
6.	735	414	—	509
7.	675	410	561	505
8.	700	412	598	502·4
9.	690	421	586	501·5
10.	635	415	—	503·8
11.	718	406	570·5	491·9
12.	665	429	589·5	496·6
13.	730	410	605	502·4
14.	675	413	582	497
15.	743	400	593	507·5
16.	710	412	555	496·5

It will be noticed that the point of greatest luminosity for the four cases in which the spectrum is longest at

the red end is on an average 600. König[1] found that it was 605 for five normal sighted persons. I find like König that though the neutral point is usually nearer the violet when there is shortening of the red end of the spectrum, that this does not form a means of distinguishing between these cases. It will be seen that cases of all kinds are found from those who have a spectrum of normal length to those who have considerable shortening of the red end of the spectrum.

All those who made the observations just recorded were accurate observers and the examination with the spectrometer gave the key to their colour vision.

The following series of cases were examined by my spectrometer in the manner described. Each observer was told to pay attention only to differences of hue and saturation and not at all to differences of luminosity. It must be noted that the number of regions marked out as monochromatic does not by itself give the degree of colour perception of the observer. For instance, the first dichromic given has marked out thirteen regions, but it will be noticed these are all in the neighbourhood of the neutral region and it was not till this region was nearly reached that he noticed a colour difference. A portion of spectrum which occupies the whole of the field is first shown so that the observer may have no clue as to the position of the colour shewn him. The point to note specially is when the first trace of the second

[1] A. König, *Graefe's Archiv. für. Ophthalm.*, Bd. 30, (2), S. 155, 1884, und Wiedemann's *Annalen*, Bd. 22, S. 567, 1884.

sensation is found mixed with the first. All the cases were examined in similar conditions, the eye being light adapted in each case and the luminosity 180 meter-candles. The first column gives the number of the regions distinguished, the second the wave-length in millionths of a millimeter, the third the size of the monochromatic region in millionths of a millimeter and the

1.

	λ	δλ	
1.	724 518	206	Red.
2.	518 514	4	Yellow.
3.	514 510	4	Yellow.
4.	510 507	3	Yellow.
5.	507 504	3	Yellow.
6.	504 500	4	Yellow.
7.	500 497	3	Green.
8.	497 495	2	Green.
9.	495 491·5	4	Green.
10.	491·5 482	9	Blue-Green.
11.	482 436	46	Blue.

Length of Spectrum, 288.

2.

	λ	δλ	
1.	780 675	105	Red.
2.	675 634	41	Red.
3.	634 534	100	Yellow.
4.	534 512	22	Yellow.
5.	512 501	11	Yellowish.
6.	501 496	5	No Colour.
7.	496 490	6	Blue-Green.
8.	490 482	8	Blue-Green.
9.	482 409	73	Blue.

Length of Spectrum, 371.

3.

	λ	δλ	
1.	775 653·5	122	Red.
2.	653·5 517	136	Yellow.
3.	517 506	11	Green.
4.	506 494	12	Green.
5.	494 484	10	Blue.
6.	484 473·5	11	Blue.
7.	473·5 416	57	Blue.

Length of Spectrum, 359.

4*a*. 180 Meter-candles.

	λ	δλ	
1.	680 506	174	Orange-Yellow.
2.	506 500	6	Yellow-Grey.
3.	500 495	5	Yellow-Grey.
4.	495 492	3	Grey.
5.	492 487	5	Blue-Grey.
6.	487 482	5	Blue.
7.	482 420	62	Blue.

Length of Spectrum, 260.

4*b*. 2·6 Meter-candles.

	λ	δλ	
1.	650 501	149	Red-Yellow.
2.	501 489	12	Grey.
3.	489 461	28	Blue.

Length of Spectrum, 189.

5

	λ	δλ	
1.	730 509	221	Yellow.
2.	509 505	4	Green.
3.	505 497	8	Green.
4.	497 493	4	Blue-Green.
5.	493 489	6	Blue-Green.
6.	489 426	63	Blue.
7.	426 410	16	Blue.

Length of Spectrum, 320.

6.

	λ	λδ	
1.	780 536	244	Yellow.
2.	536 502	34	Yellow.
3.	502 493	9	Yellow.
4.	493 486	7	Yellow.
5.	486 480	6	White.
6.	480 395	85	Blue.

Length of Spectrum, 385.

7.

	λ	δλ	
1.	735 605	130	Yellow.
2.	605 534	71	Yellow.
3.	534 499	35	Yellow.
4.	499 492	7	Green.
5.	492 482	10	Blue-Green.
6.	482 414	68	Blue.

Length of Spectrum, 321.

8.

	λ	δλ	
1.	675 510	165	Red.
2.	510 500	10	No Colour. Red-Green.
3.	500 489·5	10	Green.
4.	489·5 479	11	Blue-Green.
5.	479 410	69	Blue.

Length of Spectrum, 265.

9.

	λ	δλ	
1.	700 526	174	Orange.
2.	526 509	17	Orange.
3.	509 501	8	Bluish- Yellowish.
4.	501 491	10	Blue-Grey.
5.	491 412	79	Blue.

Length of Spectrum, 288.

10*a*. 180 Meter-candles.

	λ	δλ	
1.	690 506	184	Red.
2.	506 493	13	Reddish-Grey.
3.	493 487	6	Bluish-Grey.
4.	487 421	66	Blue.

Length of Spectrum, 269.

10*b*. 2·6 Meter-candles.

	λ	δλ	
1.	647 530	117	Red.
2.	530 514	16	Greyish-Red.
3.	514 503	11	No colour.
4.	503 438	68	Purple.

Length of Spectrum, 212.

11.

	λ	δλ	
1.	635 503	132	Yellowish-Red.
2.	503 494	9	Yellow-Green.
3.	494 482	12	Blue-Green.
4.	482 415	67	Violet.

Length of Spectrum, 220

12.

	λ	δλ	
1.	718·5 509	209	Red-Greyish.
2.	509 498	11	Yellow.
3.	498 488	10	No colour.
4.	488 406	82	Blue.

Length of Spectrum, 312.

13.

	λ	δλ	
1.	675 494	181	Yellow.
2.	494 487	7	Pale-Blue.
3.	487 413	74	Blue.

Length of Spectrum, 262.

14.

	λ	δλ	
1.	665 498	167	Yellow.
2	498 429	69	Blue.

Length of Spectrum, 236.

fourth the colour name given to the region. In every case there was no doubt about the dichromic vision and all had when examined with my lantern confused red, green, and yellow in appropriate conditions.

Varieties of Dichromic Vision.

In addition to the varying hue perception which is found with different dichromics there may be associated defects of light perception. There may be shortening of the red or of the violet end of the spectrum; there may be defective perception for some of the other spectral rays; the luminosity curve may have its maximum at a different place to the normal; there may be defective perception when the image on the retina is diminished in size; and the size of the neutral region is very variable. All these defects produce their characteristic symptoms. Of the large number of cases which I have examined I have not found one which when examined in the manner I have described would support the older theories. It can be easily shown that the defect which has caused the non-perception of certain rays has not caused the dichromatism. For instance, the red may be shortened to $\lambda 680$; at $\lambda 670$ the perception of red may be defective to about half the normal, and at $\lambda 660$ it may be quite normal. If we now test such a case with spectral colours from $\lambda 660$ onwards to the violet end of the spectrum, we find that their luminosity, *i.e.* differences of light and shade, is identical with the normal. Thus the subtraction of the element

which causes the non-perception of certain rays cannot be responsible for the dichromic vision which extends from $\lambda660$ to $\lambda385$.

In estimating defects of light perception, colours should be directly compared in order to ascertain their comparative luminosities. For instance, light of $\lambda589$ can be compared with light of $\lambda570$ and $\lambda535$. A comparison with white light gives rise to results which are very fallacious. Not only have the missing red rays to be subtracted, but if the individual have a spectrum which is lengthened at the violet end or is more sensitive to any other rays than the normal, a co-efficient corresponding to these rays must be added. Therefore, if α represent the missing red rays and β the added violet rays, the formula of white light as seen by the individual in question, as compared with the normal, will be white $-\alpha+\beta$.

Still more difficult to explain on any light perception theory are the cases of so-called green blindness. These, as I have shown, are simply cases of dichromic vision without shortening of the spectrum, and, indeed, with no defect in light perception in any part of the spectrum. If to such persons we give colours to compare which differ only slightly in shade but are absolutely different in hue, we find that their selection of the lightest or darkest corresponds to that which would be made by a normal individual. A red and a green, or an orange and a green, will be selected which to the normal eye match exactly in shade. I have also examined a dichromic

of this kind with faint green lights; these were viewed from a distance through blue-green glasses so that all light supposed to affect the hypothetical red sensation chiefly should be cut off, but the lights were visible to him up to their point of disappearance for me.

The varying size of the neutral region causes different symptoms. When this is extensive only violet and red may be seen in the spectrum, yellow, blue, and green being confused with each other and with grey and purple. A case of this kind at first sight appears to be one of the so-called blue-yellow blindness, but it must be noted that both colours are confused with green. A common mistake of a person of this kind is to confuse a sovereign with a shilling.

Nature of the Two Colour Sensations of the Dichromic.

There has been much discussion as to the nature of the two colour sensations of the dichromic, whether they correspond to any of the normal colour sensations or whether they are quite distinct. In dichromic cases in which only two colours are seen in the spectrum it is obvious that any portion included in the monochromatic area might be taken to represent that area. If in the evolution of the colour sense the first two colours to be discriminated were red and violet, these two colours should be most representative of the two colour sensations. I am now convinced that this is the case and that the two colours seen correspond to a red and a violet with less colour difference between them and less saturated

colours. Two cases which I have examined throw light upon this point. One was colour blind with one eye only and he said that he saw the spectrum with this eye as nearly all grey but with a tinge of red at one end and a tinge of violet at the other. The other case was a woman who had become totally colour blind as a sequel of ear disease. She was sent to me when she had regained a certain amount of colour sensation. She also saw the spectrum nearly all grey with red at one end and violet at the other. In those congenital cases in which the two sensations are separated by a wide neutral portion the observer emphatically declares that the two colours which he sees are red and violet.

In other cases in which there are several differences of colour to be seen in each of the two divisions of the spectrum there is more difficulty. Many dichromics of this kind declare that yellow and blue are the two colours which they see in the bright spectrum. I also stated in my earlier writings that yellow and blue were the two most representative colours because of their superior luminosity and the fact that they occupy central positions in the two colours. When no colour difference is seen between red and yellow either colour may be chosen when both are of the same luminosity. When, however, a colour difference is seen an increased colour saturation may be made visible in the red when this is increased in luminosity, which shows definitely that red and violet are the two colours presenting the greatest difference. In fact, I find that most acute

observers express the opinion that though yellow may be the brightest, red has the most colour in it of the same kind. I will give an illustration of this from the writings of Pole,[1] a so-called red blind. I do this more readily because Pole was one of the strongest advocates of the view that the two sensations of the dichromic are yellow and blue, so that observations made by him against this view are particularly convincing. He writes referring to the change in the appearance of red in gaslight compared with daylight.

"The change in the lighter reds is very astonishing; and the full red by gaslight is to me a most 'superb' colour. Dalton could never bring himself to believe it was really a yellow sensation. I have heard other colour-blind persons declare it to be a red which only appears in that way; and although I myself cannot detect any new colour sensation in it, I am obliged to admit that, as yellow, it is extraordinarily saturated and powerful. There seems something about this change that deserves further inquiry."

In gaslight there is an increased proportion of red rays compared with daylight.

The case of Dr. Pole illustrates the artificiality of the division into red and green blind. He writes that Maxwell said he was red blind, but on sending his match to Holmgren the latter declared that he was green blind. I examined him and came to the conclusion that he was a simple dichromic and this is the opinion he himself

[1] *Trans. Royal Soc. of Edin.*, 1893, p. 447.

held. I examined him particularly with regard to luminosity. I tested him with some wools which were very nearly alike in shade, and in each case he pointed out the darkest correctly. Shades of red and green; and green and violet were matched. I have given an account of his case in my book.[1]

Summary.

1. There are many degrees and varieties of dichromic vision.

2. There are not two well-defined varieties of dichromic vision, there are innumerable gradations connecting the two.

3. In many cases precisely the same errors are made both by those with and those without defective perception of red, when the rays for which there is defective perception are not involved.

4. All dichromics are not equally colour blind, that is, one may have a much better hue perception than another.

5. Dichromic vision may be associated with defects of light perception which are also found in cases in which the vision is not dichromic.

6. Dichromics may have a perception of shade and a luminosity curve similar to the normal.

7. Many dichromics match very accurately, their colour perception being sufficient for the purpose when the colours are not too close in the spectrum.

8. The degree of colour blindness varies with the state of health.

9. Colour discrimination is diminished as a whole in dichromic vision.

10. Dichromic vision appears to be due to a defective power of colour differentiation, probably corresponding to an earlier state in the evolution of the colour sense.

11. The two colours seen are red and violet.

[1] *Colour-Blindness and Colour-Perception*, Int. Scient. Ser., 1909, p. 188.

Trichromic Vision.

Persons belonging to this class have three definite colour sensations, red, green, and violet. They behave in every way as if they only possessed three definite colour sensations: they describe the spectrum as consisting of red, red-green, green-violet, and violet. The orange and yellow regions are described as red-green and the blue region as green-violet. A very good idea of the appearance of the spectrum to the trichromic can be obtained by a normal sighted person by viewing a spectrum of diminished intensity: this spectrum appears to consist of only three colours, red, green, and violet. If a trichromic be examined with my spectrometer he will mark out about half the number of monochromatic divisions made by the hexachromic. In the examples which I have given it will be seen that these are ten in each case. When a curve is constructed from these divisions it will be seen that it has the same general shape as the normal and that the hue perception is defective in every part. These cases are partially colour blind, but generally pass those tests which in past times were used for the detection of colour blindness. Any normal sighted person examining the monochromatic regions marked out by a trichromic declares most emphatically that the latter is colour blind. The trichromic, for instance, will isolate a region with my spectrometer which contains orange-yellow, yellow, and greenish-yellow and declare that the whole is absolutely uniform, and could be represented with one brush

of colour. They will rarely be detected by the Holmgren test, especially if they have had an opportunity of studying it or of watching a normal sighted person going through it. It is quite different when they are asked to name colours. Then great difficulty is found with yellow and blue. A yellow placed adjacent to a green is called red and a yellow placed adjacent to a red is called green. When examined with my lantern this colour blindness is strikingly evident, the mistakes made depending upon the degree of the defect. In all cases there is considerable difficulty with yellow; when a yellow is seen after or adjacent to a red it is called green, and when it is seen immediately after or adjacent to green it is called red. In cases bordering on the dichromic, dichromic mistakes will be made with feeble colours and those occupying a small visual angle. Those bordering on the tetrachromic make fewer mistakes.

Simultaneous and successive contrast are increased in the trichromic. This we should expect as they regard yellow as red-green; any change by contrast must make it more green or more red as the case may be and therefore liable to be mistaken with a colour to which its hue apparently approaches. As discrimination is diminished this increase of simultaneous and successive contrast only becomes evident when a difference is seen.

An important point to note is that just as with the normal sighted and other degrees of colour perception, the trichromic discriminate colours better with the fovea than with surrounding regions of the retina. This is

Monochromatic Divisions in Wave-lengths as Marked out by Trichromics 1, 2, *and* 3.

No. of patches.	Case 1.		Case 2.		Case 3.	
	λ.	δλ.	λ.	δλ.	λ.	δλ.
1	7341 6160	1181	7604 6149	1455	7604 6105	1499
2	6037 5877	160	6050 5877	173	6032 5877	155
3	5873 5677	196	5883 5694	189	5877 5765	112
4	5679 5408	271	5694 5453	241	5765 5660	105
5	5411 5309	102	5446 5166	280	5660 5529	131
6	5309 5178	131	5166 4991	175	5529 5323	206
7	5176 5070	106	4991 4916	75	5326 5024	302
8	5070 4969	101	4921 4855	66	5024 4855	169
9	4972 4806	166	4850 4713	137	4850 4713	137
10	4811 4019	792	4713 3853	860	4713 3853	860
	Length of spectrum, 3322 Ångström units.		Length of spectrum, 3751 Ångström units.		Length of spectrum, 3751 Ångström units.	

δλ represents the size of the monochromatic area in Ångström units.

strikingly shown by the use of the card test, single spots may be picked out whilst the examinee is quite unable to read the letter and even has difficulty in again picking out the spot which he has recognised as different.

On comparing these three cases, it will be noted that there is a series of very remarkable coincidences. Each presents 10 monochromatic divisions, and in each these are largest at the extremities and centre. It will be noticed also that the smaller divisions are grouped round the central one. In 1 and 3 there are in each case five intermediate divisions on one side and two on the other, but in 1 the five divisions are on the violet side and in 3 on the red side.

As far as these intermediate regions are concerned, 3 looks like a reversal of 1. No. 2 has four divisions on one side and three on the other. There are also coincidences in the wave-lengths. The first two divisions on the violet side in 2 and 3 are exactly alike in size and position. All three coincide at $\lambda 5877$. Nos. 2 and 3 have a spectrum of normal length and of exactly the same size, whilst 1 has a spectrum which is shortened at both ends but more shortened on the red side. The centre of the smallest division of 1 is $\lambda 5543$, and the centres of 2 and 3 $\lambda 5306$ and $\lambda 5174$ respectively. It would appear as if these were three similar cases with different absorption.

We know that the portions of the spectrum which differ are those which are most influenced by the varying pigmentation of the yellow spot. It will be noticed

that the total effect is the same, the spectrum being divided into 10 divisions in each case, so that what is gained on one side is lost on the other. No. 2 is the spectrum of Sir J. J. Thomson, further details of whose colour perception I have given in the *Proceedings of the Royal Society*, B, vol. 76, 1905, p. 194. Sir J. J. Thomson, when making the match previously mentioned with Rayleigh's apparatus, put more green than the normal in the mixed colour, but the other two trichromics made the normal match. It is obvious that this alteration in light perception could not produce the defect in colour perception which was found.

Tetrachromic Vision.

The tetrachromic see four distinct colours, red, yellow, green, and violet in a bright spectrum; they designate the blue region of the normal sighted as violet-green. It will be seen, therefore, that they have four colour sensations instead of six as they do not regard blue and orange as distinct colours. When they do use the term blue, as is often the case and they are told to select in the spectrum the most typical blue, they will select a region of pure violet. They can be made to match blue and violet and will regard both as identical when a difference is plainly visible to normal sighted persons. The region of the spectrum which they select as pure yellow is orange-yellow to the normal sighted.

The tetrachromic form the border line of rejection in those employments in which it is necessary to dis-

tinguish between red, yellow (white) and green. When examined with my spectrometer they will mark out a greater number of monochromatic regions than the

Wave-Length in $\mu\mu$.	Size of Monochromatic Region in $\mu\mu$.	
λ		$\delta\lambda$
780		
1	1	145
635		
1	2	17
618		
1	3	19
599		
1	4	9
590		
1	5	22
568		
1	6	61
507		
1	7	12
495		
1	8	9
486		
1	9	13
473		
1	10	25
448		
1	11	45
403		

trichromic and a less number than the pentachromics according to the degree of the defect. They will, for instance, mark out from eleven to fourteen, according

to the degree of the defect, instead of the eighteen which are marked out by the hexachromic. On page 201 are monochromatic regions marked out by a tetrachromic who was bordering on the trichromic.

Any hexachromic examining these pseudo-monochromatic regions would declare that the tetrachromic was decidedly colour blind. Let us, therefore, consider his examination with other tests. Examined with the new Board of Trade improvement of Holmgren's test [1] in which there are five test colours—and the test is made much more like my classification test—he matched all the test colours as easily and naturally as a normal sighted person. He did not touch a confusion colour. Examined with the last edition of Nagel's test, he passed this as easily and accurately as a normal sighted person. He had not been examined with it nor seen the test before.

Examined with my colour perception lantern, he called green white, when seen after signal green or blue, and yellow red, and called signal green purplish-green, and neutrals 1, 2, and 3 light green. He named red, green, and white correctly through the 1000 yards aperture, but when examined again after the other examinations, could not see red B when it was plainly visible to me; he saw a spot of light but no colour, and had to walk half the distance before he saw a colour and then saw it as red. He also saw green as a spot of light before he saw it as a colour. He did not on any occasion confuse red and green. On a subsequent occasion

[1] Now rightly discarded.

I examined him at night on the railway and with other lights. When at a distance he continually called the white (yellow) lights, green, especially when they were adjacent to red. He called blue lights, green, and several green lights, especially yellow-green lights, white.

The tetrachromic form the large class of those who, whilst not appearing to be colour blind by many tests, are in continual difficulty over blue. A colour which is definitely seen as blue by the normal sighted is called by them green, and yellow-green may be called blue if seen after red. The point of view of the tetrachromic is that of a well known artist who was declaring to some other artists that there was no such colour as blue, and that all blues were either green or violet in varying proportions. None of his hearers agreed with him. When I have asked a tetrachromic to paint a picture from a copy he has represented blue and green uniformly by green. The colour perception of the tetrachromic is diminished as a whole and those cases which border on the trichromic have a more defective colour perception than those which border on the pentachromic. For instance, most tetrachromics distinguish easily the red, green, and white lights of my lantern with an aperture corresponding to a light on a railway at a 1000 yards when tested at 20 feet. When, however, a person is bordering on the trichromic, as in the case I have related, he makes mistakes of the trichromic when the coloured objects are small, dark, or of feeble saturation.

The fact that blue is called green by the tetrachromic is well shown by asking the names of the shadows coloured by contrast; whilst the shadow adjacent to blue is called correctly yellow, that caused by yellow is called green instead of blue. This can be easily tried with a shadow on a sheet of white paper thrown by a pencil, a piece of coloured glass being interposed between the paper and the light. All the shadows are correctly named, with the exception of that of the yellow glass. Common mistakes which are made by the tetrachromic are calling a blue inclining to violet greenish-purple or greenish-violet, or blue-green, and light red or orange, yellow. Simultaneous and successive contrast are increased compared with the hexachromic, but yellow being correctly recognized, this is not so evident as in the case of the trichromic.

It will be seen that this case has only one more monochromatic division than the trichromic and the point for consideration is, should he or should he not be rejected? If the slightest degree of colour blindness which can be detected be rejected then we shall have to reject the pentachromic as well as those with small degrees of shortening of the spectrum because neither of these have as good colour perception as the normal. The point, however, is, have they a sufficient colour perception for all practical purposes?

It is quite obvious that they are not as efficient as those possessing a better colour perception.

Pentachromic Vision.

The pentachromic see five definite colours in the bright spectrum, red, yellow, green, blue, and violet. They usually express the opinion that the term orange is a hair-splitting distinction and can be properly described as yellowish-red. Orange-yellow is usually selected as the region of pure yellow. They mark out a less number of monochromatic regions than the hexachromic and a greater number than the tetrachromic. The marking out does not appear satisfactory to the hexachromic. When the figures corresponding to the regions are formed into a curve it has the same general shape as the hexachromic, that is to say, the larger regions are at the ends and the centre and the smaller between them. Colour as a quality is lessened to the pentachromic, they fatigue more readily than the hexachromic and are more readily reduced to a lower degree of colour perception. They find more difficulty in distinguishing between colours than the hexachromic. This is particularly noticeable when they are asked to name single colours. Their defective perception for orange is shown by their not being able to tell whether a strontium flame which is red or a calcium flame which is orange is being shown.

II. Abnormalities and Defects of Light Perception.

As methods of investigation improve and multiply in number so do the number of ascertained deviations from the normal increase. A person may be normal

with five methods of investigation and on examination with the sixth be found to present considerable variation from the normal with that particular method. Slight deviations we should of course expect and it is improbable we should find two exactly alike any more than we should find two people with features identical in every respect. We should also expect that there would be considerable deviations in one or other of the special visual functions as there are so many factors to be taken into consideration. Light has to be changed into a visual impulse and this impulse has to travel along a chain of neurons each of which must have its special function. According to the development of each special neuron will its function be well or imperfectly performed. Abnormalities and defects of light perception may be subdivided as follows :

1. Increase or diminution in the visible range of the spectrum.
2. Defective sensibility for certain wave-lengths.
3. Increased sensitiveness for certain wave-lengths.
4. Variations in the maximum of the luminosity curve.
5. Increase or defects in the power of dark adaptation.
    (*a*) Very rapid or slow dark adaptation.
    (*b*) Very complete or imperfect dark adaptation.

It will be noticed that I have drawn attention to the superiority over the majority which exists in some persons and I think that these persons might well be employed in positions in which this superiority is a special benefit to their fellows.

(1) If a number of persons be examined with a bright spectrum as to the point when they first see light where the red commences and the point where violet terminates, it will be found that there are considerable variations in different cases.

Rählmann[1] found about 33 per cent. of those whom he examined to be defective in this respect.

Shortening of the spectrum may be found for bright light or only for light of diminished intensity. The shortening may also be abrupt or more or less diffuse, that is, there may be defective perception of red or violet over a much larger area. The light perception may be absolutely normal immediately adjacent to the portion where there is defective light perception. For instance, the red may be shortened to $\lambda 680$, at $\lambda 670$ the perception of red may be defective to about half the normal and at $\lambda 660$ it might be quite normal. This can be proved with a colour-mixing apparatus with the equation $\lambda 670 + \lambda 535 = \lambda 589$. If red $\lambda 660$ be substituted for red $\lambda 670$ an absolutely normal match will be made; if red of $\lambda 670$ be used twice as much red will be put in the mixed colour as with the normal and if red of $\lambda 680$ be used a match is quite impossible in any circumstances.

The following is a case of defective light perception with normal colour perception.

As an illustration of this class I may mention a case in which there was shortening of the red end of the spectrum with absolutely normal hue perception. A

[1] *Zeitschr. f. Augenh.*, xvi. S. 448.

boy wishing to enter the Navy had been examined with the Holmgren test and certified to have normal colour perception. He was rejected, however, with the lantern test. He was then sent to me. I found his hue perception quite normal. He matched and named colours with ease and accuracy. When tested with the spectrometer, however, I found that his spectrum for bright light was shortened to $\lambda 700$, the limit for normal individuals being about $\lambda 760$ to $\lambda 780$. He had also defective perception for the red rays adjacent to the shortened portion. When examined with my lantern he failed altogether to see the standard red light (Red A) at about 20 feet distance, though he could clearly see the aperture through which the light came. The bright red light consisting almost exclusively of rays from $\lambda 625$ to $\lambda 731$ was not even visible to him as light, though I used the largest aperture.

In the reports of the Board of Trade there are several cases of men who have passed the green test of Holmgren, but have failed with the rose test and have therefore been designated completely red-blind. These cases are probably similar to the boy whose condition I have just described. Such cases are undoubtedly red-blind for the rays which are not seen, but not in the sense of the Young-Helmholtz or Hering theories. This boy was in a similar position to a person who is unable to hear very low notes on an organ. Such persons may have absolutely normal perception of tone differences above a certain number of vibrations per second, and in the

same way these cases of so-called red blindness may have a normal appreciation of colour differences for all the spectrum except the least refrangible rays, which do not influence their retinae at all. In the same way, just as certain individuals may be deaf to the highest notes of music, so there is a class of persons whose spectrum is shortened at the violet end. Although such cases will have an appreciation of colour differences as good as that of the average individual, their colour sense will not be identical with the latter.

This will be evident if we consider the influence of a shortened spectrum upon colour vision. The first evident fact is that bodies reflecting only light, the rays of which occupy the missing portion of the spectrum, appear black. Nearly all colours are compound, that is to say, the coloured body reflects other rays than those of the colour seen. Thus a blue-green glass may transmit the green, blue, and violet rays of the spectrum. Let us suppose that we have a substance reflecting the green, blue, and three-quarters of the violet, the colour of the body to a normal person being green. Then if we had another substance which reflected the whole of the violet, it would appear blue. But with a person who could not perceive the terminal fourth of the violet the colour would look exactly the same as the green one, and as he could not distinguish between the two, he would be in continual difficulty with blues and greens. All coloured objects reflecting rays occupying the missing portion appear darker than they do to the normal sighted,

and are always matched with darker colours belonging to a point more internal. Thus a dichromic with a shortened red end of the spectrum matches a red with a darker green.

It will be noticed that a shortened spectrum, especially if one end only be affected, may interfere very little with the general appreciation of shade. If, for instance, we take a case in which the red end of the spectrum is shortened, so that only three quarters of the red of the normal sighted is seen, then all bodies which equally reflect or transmit these rays can be correctly compared, because a similar portion of light has been removed from each. It is only when one colour reflects or transmits the rays occupying the shortened portion and the other does not that there is any definite interference with the appreciation of shade. Again, if neither colour reflects or transmits rays occupying the shortened portion of the spectrum, there will obviously be no interference with the appreciation of shade.

A very common mistake due to shortening of the red end of the spectrum is the confusion of pink and blue. If a person with considerable shortening of the red end of the spectrum is shown a pink which is made up of a mixture of red and violet, the red consisting of rays occupying the missing portion of the spectrum, only the violet is visible to him, and so the pink appears a violet without a trace of red. This pink is therefore matched with a violet or blue very much darker than itself.

Mistakes which are due to shortening of the spectrum

may be remedied if we subtract the rays occupying the missing portion from the colour of confusion. For instance, if we take a blue and a pink which have been put together as identical by a person with a shortened red end of the spectrum, and look at them through a glass which is opaque to the red but transparent to the remaining rays of the spectrum, both will appear alike in hue and shade. A person with considerable shortening of the red end of the spectrum will look at a red light (which is so dazzlingly bright to a normal sighted person as to make his eyes ache after looking at it closely for a few seconds), at a distance of a few inches, and remark that there is nothing visible, and that the whole is absolutely black. It is obvious that the light must consist only of rays occupying the missing portion of the spectrum.

The same remarks which I have made for a shortened spectrum apply to cases in which there is defect of light perception through absorption or any other cause. The person having the defect is placed in a similar position to a normal sighted person with those particular rays removed or reduced to the same intensity.

Another effect of shortening of the spectrum when it is sufficient to interfere with the difference perception which appears to be inherent in the central nervous system is that the colours appear to be moved in the direction of the unshortened portion. For instance, we find the neutral point of the dichromic with shortening of the red end of the spectrum further towards the violet

end of the spectrum in comparison with a case in which the spectrum is of normal length. In the same way a trichromic with a shortened red end of the spectrum has the junction of the red and green nearer the violet end than in a case where there is no shortening.

The point that I specially wish to emphasise is that, though every case in which there is defective light perception can be explained by a defective sensibility to light of certain wave-length, not a single case of the very large number of persons that I have examined can be explained on the older theories, that is, the defect of light perception cannot be explained on the assumption that there is a defect in a light-perceiving substance which is sensitive to rays of light from a considerable range of the spectrum.

III. Defects of Colour Perception due to Imperfect Functioning of the Central Part of the Retina.

Examples of this kind are found in cases of central scotoma for colours. This is common in certain diseases of the eye, especially that caused by the abuse of tobacco. In cases of this kind the subject of the defect is able to recognise colours when the area is large or subtends a large visual angle, but is unable to discriminate between them when the object is small or subtends a small visual angle. Most cases of this kind when caused by disease have diminished visual acuity as well but this is not always the case. When the defect is not acquired it is not necessarily accompanied by any diminution of visual acuity.

CHAPTER XXIII.

THE EVOLUTION OF THE COLOUR SENSE.

There can be no doubt that an evolution of the colour sense has taken place. The only point is, how, and when, did this occur? It is obvious that in those low forms of animal life in which the most rudimentary sense of sight exists there can be no sense of colour. The animal which can only perceive light and shade, can only discriminate in a rough way between varying intensities of the stimulus. It is obvious, therefore, that the sense of light must have been developed first and then the sense of colour. The sense of sight must have been first developed for those waves which produced their maximum effect upon the sensitive protoplasm.

The next process of development would be for the protoplasm to become sensitive to the waves above and below those which first caused an effect. In the physical stimulus which produces the sensation of light there are two factors to be considered, the length of the wave and its amplitude, the greater the amplitude within certain limits the greater the intensity of the sensation.

The wave-length of the physical stimulus is the

physical basis of the sensation of colour. How did the sensation of colour first arrive? Let us suppose that the physiological effect of the physical stimulus differed according to the wave-length of the physical stimulus. At a certain stage the eye had become sensitive to a fair range of the spectral rays, that is to say, evolution had proceeded to the extent of making the protoplasm sensitive to rays of light considerably above and below those which first caused a sensation of light. There was then an eye which was sensitive to the greater part of the rays which form the visible spectrum. It was, however, an eye which was devoid of the sense of colour, no matter from what part of the spectrum the rays were taken. The only difference appreciated was one of intensity. There are in the physical stimulus two variables, wave-length and amplitude of the wave. Let us now suppose that a fresh power of discrimination was added to the eye and that it became able to discriminate between different wave-lengths of light. What would be the most probable commencement of development of the sense of colour? Most probably the differentiation of the physical stimuli which were physically most different. That is to say, the eye would first discriminate between the rays which are physically most different in the visible spectrum, the red and the violet, that is presuming that the eye had become sensitive to this range. We have examples of cases of defective light perception in which there is shortening of the red or violet end of the spectrum.

Let us now work out the evolution of the colour sense on the assumption that the rays which are physically most different, namely red and violet, were those which were first differentiated. We know that the various rays differ in their effects on various substances, the red rays are more powerful in their heating effects, whilst the violet are more active actinally, as is well known by the readiness with which they act upon a photographic plate.

We should now have an individual who would see the spectrum nearly all a uniform grey of different degrees of luminosity but with a tinge of red at one end and a tinge of violet at the other. There is a great deal of evidence to show that this is how the colour sense was first developed. For instance, in the degree of colour blindness just preceding total the spectrum is seen in this way.

It will be noticed in the first evolution of colour that the added power of discrimination is something distinct and separate from light perception. It can be destroyed as by mixing the two colours without interfering with the perception of light. Here we have the foundation for the distinction between light and colour perception the proper recognition of which is so essential in physiological optics. As the colour sense developed it was not necessary that the rays should be so far apart before a difference was seen, so the two colours red and violet gradually encroached on the grey band until they met in the centre of the spectrum.

We have now a series of cases each of which only sees two colours, red and violet, with a varying degree of grey band in the centre of the spectrum. We should expect that those who had the smallest white region left in the centre of the spectrum would have the best colour perception, because they belong to a later stage of evolution.

The luminosity curve should be the same as the normal sighted.

I have had cases of colour blindness corresponding to all these degrees.

I find that the cases of dichromic vision vary from almost total colour blindness to cases bordering on those I have called the trichromic.

It will be noticed that in all the dichromics a mixture of the two colours which they perceive, namely red and violet, will form white, and so we have the foundation of complementary colours.

The next stage in the evolution of the colour sense was when a third colour appeared at the third point of physiological difference, that is, in the centre of the spectrum in the position of the green.

The colour-sense now assumed a trichromic form, red, green, and violet, being seen in the spectrum.

I have examined many persons who have seen the spectrum in this way and have designated them trichromic because they see only three colours in the spectrum and describe it as consisting of red, red-green, green-violet, and violet.

As green replaced the grey which existed in the spectrum of the dichromic we should expect that green should be complementary to the other two colours combined, and this we find to be the case.

We have now reached the stage in which three distinct colours were seen in the spectrum, namely red, green, and violet, and the vision has assumed the trichromic character which must henceforth remain.

When the green was first developed it was a comparatively unimportant colour. As evolution proceeded the power of differentiation occurred in the regions between the red and the green and the green and the violet until a stage was reached in which a fourth colour, yellow, was seen at the next point of greatest physiological difference.

The next step in the process of evolution occurred when the retino-cerebral apparatus was able to differentiate a fresh colour between the green and the violet, namely blue, five definite colours being seen in the spectrum. It will be obvious that in any further evolution the intermediate portions will be still further differentiated, and so we arrive at those who can see six and seven colours in the spectrum respectively.

It is not necessary to consider the further evolution of the colour-sense, because I have not met with a person who could distinguish more than seven definite colours in the spectrum.

CHAPTER XXIV.

TRICHROMIC VISION AND ANOMALOUS TRICHROMATISM.

Those are designated anomalous trichromats who, when making the equation $\lambda 670 + \lambda 535 = \lambda 589$, use proportions of red and green different from the normal. At the same time the subjects of this abnormality object to the normal equation. Those who put too much red in the mixed colour are called red anomalies and those who put too much green in the mixed colour green anomalies.

It has been stated that anomalous trichromats were colour weak with symptoms similar to those given by me as associated with trichromic vision.

This has probably arisen from not making certain that the person examined, who makes an anomalous equation, objects to that of the normal. The colour weak will often make an anomalous equation, whilst agreeing with that of the normal.

Many colour blind persons, both dichromic and trichromic, can make a match which agrees in every particular with that of a normal sighted person.

There is also no evidence that colour weakness is necessarily associated with anomalous trichromatism.

The following is the result of an examination of a hundred women students, 25 belonging to the London County Council training college, and 75 to University College. The last 75 were examined in precisely similar conditions. The illumination was incandescent-electric light and the equation did not vary from day to day. All were examined with Lord Rayleigh's colour-mixing apparatus; 51 were examined by some kind of test for colour blindness and 36 of these were examined by my lantern. I have designated as anomalies those who on an average of a number of observations had a deviation of more than one whole division from the normal, and did not agree with the normal equation. The colour-mixing instrument of Rayleigh was arranged so that 0 corresponded to full red and 25 to full green. Then by the laws of double refraction the exact proportions of red and green in any mixture can be ascertained. For instance, 12·73 corresponds to a ratio of intensity 1·061 $\frac{\text{green}}{\text{red}}$ and 10·371 to ·5829 $\frac{\text{green}}{\text{red}}$. The other figures can be easily understood by remembering that a difference of one tenth of a division corresponds to a difference of about $2\frac{1}{2}$ per cent. in the ratio of intensities of red to green, when the figures are in the neighbourhood of normal vision.

Out of the hundred examined 86 made the normal equation or within one division on either side of it,

12 were anomalous trichromats, 10 being red anomalies and 3 being green anomalies.

Red Anomalies.

1. 1·5.	2. 1·4.	3. 1·2.	4. 1·5.	5. 1·3.
6. 1·2.	7. 1·8.	8. 2·5.	9. 1·3.	10. 1·3.

Green Anomalies.

1. 3·1.	2. 1·3.

Two others on an average of five observations appeared as anomalies (one, 1·3 red, the other 2, green), but as they both agreed with the normal equation, they do not come under the definition.

Excluding the last mentioned, who were to a certain extent, colour blind, none of the anomalies were found to be colour-defective. Of those who made the normal match 9 were found to be colour defective.

No. 1 of the green anomalies was examined very carefully on three occasions; there was no evidence of colour blindness; she passed my ordinary lantern test and also my triple lantern with ease and accuracy and saw red and green through small apertures as far as I did. She also passed my bead test. Examined with spectrometer, pure yellow was isolated at $\lambda 5770$ to $\lambda 5882$. This is quite normal. The area of greatest luminosity was $\lambda 5697$ to $\lambda 5795$, this is considerably to the green side of the maximum of the normal luminosity curve. She

marked out 18 monochromatic divisions in the spectrum. This is the normal number; she also named all the colours red, orange, yellow, green, blue, and violet correctly.

I have also examined a large number of men and find that when there is a large mean deviation there is colour weakness. The following case is instructive as an example of a high grade green anomaly without any trace of colour weakness.

The observer was an assistant in the Chemical Laboratory of the Physiological Institute, University College.

Rayleigh Apparatus.

Shown red and yellow. Named them correctly as red and yellow.

The mean of seven equations was 17·3, the mean deviation ·1, which is very small.

The normal equation was 14·5.

Strongly objected to the normal equations; said that the mixed colour was orange and the simple, yellow.

Nagel's Test and Stilling's Test. Passed both these tests with much greater ease and more rapidly than most normal sighted persons.

My Lantern Test. Passed easily.

Spectrometer.

Region of greatest luminosity. λ589-λ605.

Region of pure yellow. λ591-596·5.

My yellow region λ583-λ590 appeared greenish yellow to him. This region inclines to orange-yellow to me.

Pure blue was λ472-476. Pure green λ510-514.

Simultaneous contrast was not more marked than normal.

The following are the monochromatic regions marked out by him:

Saw below 780.

Designation by him of monochromatic region.

	Wave-length	Designation
1.	780–626	Red.
2.	626–613·5	Orange.
3.	613·5–605	Orange-yellow.
4.	605–597	Yellow.
5.	597–590	Greenish-yellow.
6.	590–579	,,
7.	579–567	Yellow-green.
8.	567–558	,,
9.	558–541	,,
10.	541–523	Green.
11.	523–516	Blue-green.
12.	516–509	,,
13.	509–503	Green-blue.
14.	503–497	,,
15.	497–491	,,
16.	491–483·5	Blue.
17.	483·5–475	Deep Blue.
18.	475–466·5	Violet-blue.
19.	466·5–457	Blue-violet.
20.	457–447	,,
21.	447–435	Violet.
22.	435–426	,,
23.	426–417	,,
24.	417–411	,,
25.	411–407	,,

It will be noticed that the region regarded by the normal sighted as orange-yellow is named and seen by him as greenish-yellow. This gives an explanation of the anomalous trichromatism. If the region to be matched appears greener than usual it will obviously require more green and less red in the mixed colour.

The Relation between Trichromic Vision and Anomalous Trichromatism.

Anomalous trichromatism should be clearly defined as the condition in which anomalous matches are made by a person who refuses to accept the normal match. Much confusion exists on this point; a person who agrees with the normal equation cannot be regarded as an anomalous trichromat even though he agrees at the same time with the anomalous matches. This is only evidence of colour weakness, inasmuch as both equations are regarded as satisfactory. There are many anomalous trichromats who are not colour weak and there are many trichromats who make absolutely normal equations. Trichromic vision in my classification is therefore not synonymous with anomalous trichromatism. There are also persons who will make the normal equation in one set of circumstances and anomalous equations in another. There are also those who will make normal equations when the red employed is λ670 but will make an anomalous equation with a red of larger wave-length, as, for instance, λ690, putting twice as much red in the mixture compared with the normal equation in similar circumstances. Anomalous trichromatism when too much red is put in the mixed colour may correspond to defect in the perception of certain red rays, namely, those employed in the mixed colour. I have shown that when there is shortening or much defect in the perception of red, the junctions of the other colours are shifted towards the violet end of the spectrum. The yellow, therefore,

corresponding to the D line is seen as a much redder colour than the normal, and if the green be more like the normal, it is obvious that more red will be put in the mixture than by the normal sighted. This shortening of the spectrum may be associated with normal vision in other respects, or any degree of defective colour differentiation; that is to say, it may be associated with dichromic, trichromic, tetrachromic, pentachromic, hexachromic or heptachromic vision. A similar condition is also found for the violet end of the spectrum.

It is obvious that a man who has shortening of the red end of the spectrum or defect in the perception of red is colour weak as far as red is concerned. Unless, however, he have defective hue perception he may make no other error than that directly connected with the defective perception of certain red rays. It is different with those who make an anomalous match in which too much green is put in the mixed colour. They may make an anomalous match without presenting any other colour defect. I have found 25 per cent. of men to be more or less colour weak, and it is, therefore, not surprising that anomalous trichromatism is frequently associated with colour weakness. The colour weak are also particularly liable to fail in making an equation; but in addition to making the anomalous equation they are in most cases satisfied with that of the normal. If, whilst the yellow remained as in the normal, the sensitiveness to green light were diminished or to red increased,

we should have an explanation of the facts. Whilst there are red anomalies who show weakness for red, there are others who do not, and these may be explained by an increased sensitiveness to green whilst the red and yellow remain as in the normal.

SUMMARY.

1. Trichromic vision is not synonymous with anomalous trichromatism.

2. Many persons with otherwise normal colour perception make an anomalous equation.

3. Many colour blind persons (dichromics and trichromics) make an absolutely normal match with no greater mean deviation than the normal.

4. Anomalous trichromatism and colour weakness are not synonymous.

5. A large mean deviation indicates colour weakness.

6. Anomalous trichromatism appears to be due to an alteration in the normal relations of the response to the three colours (lights) used in the equation. If the eye be more or less sensitive to one of the components of the mixed colour whilst the other has its normal effect, an anomalous equation will result. An anomalous equation will also result when the yellow is more allied to green or red than is normal.

CHAPTER XXV.

THE POSITIVE EFFECT OF STIMULATION OF THE RETINA ON SURROUNDING REGIONS.

This effect has been very generally overlooked though it is of great importance in nature and in certain instances will overcome the effect of simultaneous and successive contrast.

If a black surface from which no light is reflected, be surrounded by spectral light of any colour, the black surface will appear of the same colour as that surrounding it and steadily increasing in luminosity. In no case is there the least appearance of the complementary colour unless the eye be slightly moved, and then it is seen on the black surface. This experiment can be made equally well with a deep red glass, which does not transmit any yellow or green rays. If on a sheet of such red glass, an opaque black patch an inch square, be pasted and this be held up to the light and intently regarded with one eye, the black surface will appear uniformly red of steadily increasing luminosity. The complementary blue-green will only appear when the eye is moved.

This positive effect is very easy to see when once pointed out. The wallpaper on which pictures are hung,

greatly influences the pictures. For instance, if a green wall-paper be used the pictures may be so flooded by green as to spoil the effect. A picture of a cornfield may appear so green as to look quite wrong. The eyes in a portrait are greatly influenced by the colour of the dress. This is very easy to demonstrate. If a face be painted with eyes of a neutral grey, and arranged so that the dress of the figure can be changed to either brown or blue, when the figure is wearing a blue dress the eyes are a striking blue, but when wearing the brown dress of an equally definite brown. This also explains the Phenomenon of Colour Conversion by Stevens,[1] in which a square of red for instance placed within a square of green disappears on looking fixedly at it, the whole becoming green.

After-Images demonstrate the positive effect very definitely. If, for instance, we look at a mosaic made up of red and white and then close the eyes and cover them with the hands the white portions are seen as a brilliant red positive after-image, whilst in many cases the red portions are only seen as a negative black.

If a piece of white paper about three inches square be placed upon a piece of coloured paper, a small black dot having been made in the centre of the white paper, and this be viewed for three seconds and then the gaze be transferred to a large sheet of white paper of exactly the same nature as that occupying the centre of the coloured paper an after-image of the white paper will

[1] *American Medical Association, Chicago*, 1906.

be seen of the same colour as the coloured paper, but darker than the white paper.

This experiment may be made with spectral colours or with a lantern with coloured gelatine and a white centre.

If in a dark room a small light be exhibited it will be noticed that a luminous radiance extends for a considerable distance round the light, and of the same colour as the light. This disappears when an opaque object is placed between the light and the eye. An important fact to notice is that when the light is first exposed it appears to extend rapidly outwards.

The positive effect can be seen very clearly on those advertisements in which there is a rectangle of colour on a black ground and letters in white enamel extending through both the coloured and black rectangle. It will be noticed that where the white enamel letters extend through the coloured ground they are tinted with the same colour as this ground.

The flow of photo-chemical liquid from the periphery to the centre of the retina gives such a complete explanation of the positive effect that it seems scarcely necessary to consider any other especially as we know that this occurs and must produce an effect. It may be well, however, to deal with two other explanations which might be suggested, namely, that the effect is due to stray light, or that it is the complementary of a colour induced on a white region.

If a piece of white cardboard three inches square, be

placed on a piece of blue paper, six inches square, and the whole be placed on a large sheet of red paper twenty-four inches square, and the eye be fixed on a point in the centre of the white paper at a distance of about two feet, on moving the eye towards the white only a blue centre is seen. When two colours are used the correct colours are seen on their respective sides.

If a white triangle be surrounded by red, except on one side, and that by blue, on moving the eye closer to the white a red triangle with a blue edge corresponding to the side next blue will be seen.

The following experiment proves conclusively that the red colour cannot be the complementary of an induced blue-green. A piece of white cardboard two inches by two and three-quarters is placed on a deep red ground, the red being the brightest and purest red obtainable. It is looked at through a brown cardboard tube, two feet six inches long, and of a diameter of two inches from a distance of three feet six inches ; on approaching six inches nearer a red square is seen as before, surrounded by white without a trace of blue-green.

CHAPTER XXVI.

SIMULTANEOUS COLOUR CONTRAST.

The subject of simultaneous colour contrast presents exceptional difficulties because of the number of factors to be taken into consideration. It is necessary to eliminate the effects of successive contrast. Many of the results which have been put down to simultaneous contrast are really due to successive contrast. The surfaces to be compared should either be viewed by a flash of light of very short duration or by one eye, which is kept rigidly fixed upon a definite point.

When colours are contrasted there are four definite effects each of which has to be eliminated before the others can be estimated.

1. Chromatic Aberration.

2. The flooding effect due to the photo-chemical stimulus being liquid in the retina and affecting surrounding regions. (See Chapter 25.)

3. Simultaneous Contrast.

4. Successive Contrast.

In order, therefore, that the effects of simultaneous contrast should be correctly ascertained, two small areas of spectral colours should be viewed with one eye

in an instrument in which all other light is carefully excluded. The contrasting colours should be small rectangles which just touch, and if one rectangle be projecting above the other, which projects below; the changes in the contrasted portions become plainly evident. It will be seen that the only pairs of colours which do not alter in hue when contrasted are green and rose, and red and violet. The other colours alter as follows: When both colours lie within the spectrum, and neither are terminal colours (that is red or violet) each appears as if it were moved more towards the end of the spectrum furthest away from the other colour. The change of colour in simultaneous contrast is always greatest with colours occupying closely adjacent positions in the spectrum scale. The effect of contrasting blue-violet with violet, or orange-red with red is greater than that of contrasting any other spectral colour with the terminal colours. The effect of contrast is in direct proportion to the nearness of the colours.

In a series of papers Hering[1] has shown that the explanation of contrast given by Helmholtz is not tenable. I hope to show that another explanation is possible which is even more in accordance with the facts. I propose to review some of the experiments of Hering and to show that in conditions in which, according to the requirements stated by him, colour should be visible no colour is to be seen.

In experiments on simultaneous contrast it is

[1] *Pflüger's Arch.*, 1886, 1887, 1888.

necessary in order to avoid effects of luminosity contrast to have the two surfaces as nearly as possible of the same luminosity.

It is also necessary in dealing with mixed colours, such as those formed by the light reflected from pigments to take into consideration the effects of chromatic aberration. When a surface reflects lights of different wavelengths these lights are not all brought to the same focus on the retina. Diffusion circles will extend on both sides of the image of the coloured object on the retina and will influence the colour of another image immediately adjacent. I have made a mosaic of small pieces of coloured cardboard and the effect of the mixture of lights is very noticeable. In general each colour differs as it would do if the other colour had been objectively added to it. These colour changes have been mistaken for effects of simultaneous contrast.

Coloured Shadows.

In the classical experiment which has been the subject of so much discussion an opaque object is placed upon a white surface and illuminated on one side by daylight and on the other by a candle or petroleum lamp. By moving the candle the relative luminosities of the two shadows can be so adjusted as to appear similar in brightness.

The shadow thrown by the candle and which is illuminated by daylight appears blue, whilst that formed by the daylight and illuminated by the reddish-yellow

candle light appears yellow. It will be noticed that the shadow of the candle which is illuminated by white daylight is really grey, as it is only illuminated by a white light. Helmholtz and Hering, therefore, have referred to the blue coloration of the shadow as the subjective blue. I propose to show that the blue coloration of the shadow is relatively objective blue in the circumstances of the experiment.

It must be noted that the white surface on which the opaque object is standing and which is free from any shadow is illuminated by both daylight and candle light. Though it is still considered as a white surface it is really objectively yellow, to the extent of the added amount of candle light in the total amount of candle light and daylight which is reflected from the white surface, the degree of objective yellowness amounting to the difference between candle light and daylight in the proportion of the two. The blue shadow is therefore relatively blue in comparison to this white surface reflecting both lights when this surface is set up as a standard of white. In the same way the yellow shadow is relatively yellow in comparison to the whole surface. It must be noticed that daylight is not a fixed unalterable white but differs considerably according to the time of day and source; the light reflected from the sky is much bluer than that of direct sunlight.

All our estimations of colour are only relative and formed in association with memory and the definite objective light which falls upon the eye. In many of

the most striking contrast experiments the colour which causes the false interpretation is not perceived at all; for instance, if a sheet of pale green paper be taken for white a piece of grey paper upon it appears rose-coloured, but appears colourless when it is recognised that the paper is pale green and not white.

If, in repeating the experiment with coloured shadows, the opaque object be placed upon a dull black surface and two pieces of white paper be placed on this surface for the shadows, care being taken that these pieces of paper are the exact size of or smaller than the shadows, these will appear blue and yellow as before. If we now place a small dot on the paper on which there is a blue shadow and having covered one eye keep the other rigidly directed at this black spot whilst an opaque object is placed in front of the candle so that it no longer illuminates the paper or throws a shadow, both pieces of paper will appear white, being illuminated only by white daylight. The eye being still kept rigidly directed on the spot on the paper, the opaque object is removed so that the candle again throws a shadow on the paper. The shadow thrown by daylight immediately appears yellow and of greater saturation than before, but the shadow thrown by the candle appears white as before, and without the faintest trace of blue or blue colour. The conditions are in every way favourable to the development of the blue colour, but none appears because the observer has been able to form a correct estimate of white. If the blue colour were a real

subjective coloration caused by the yellow, blue should appear on the shadow from the candle.

The second experiment which is considered by Hering is that in which a small piece of grey paper is placed in the centre of a large square of coloured paper, and the whole is covered by a thin piece of tissue paper. The centre grey square becomes tinged of the complementary colour of the larger square on which it is placed. This experiment succeeds best when the colour of the ground is green. The grey paper is then tinged with the complementary colour, rose. This experiment, like most others of simultaneous contrast, has its effect much heightened if successive contrast be allowed to influence the result. In successive contrast the eye becomes fatigued for the colour particular to the rays of light which fall upon it.

I agree with Burch[1] that fatigue of the eye for any one colour does not increase its sensitiveness for any other colour. For instance, if the eye be fatigued for yellow the blue of the spectrum is considerably diminished not increased. This is probably due to luminosity contrast.

In the above experiment, therefore, it is very important that the eye should not see the grey square after having observed the green, as in that case it will be tinged with rose colour from successive contrast, because the eye has become fatigued for the green constituent of the white light reflected from it.

[1] *Phil. Trans.*, B. 1899, p. 5.

As is well known, the rose coloration is greatly diminished by using black or white instead of grey, or by isolating the grey square by drawing a black line round it. If, however, taking the greatest care that the eye be not moved, by steady fixation of the eye upon a black spot in the centre of the square for 10 seconds, and then looking at a sheet of white paper, a definite after-image is seen, a large rose-coloured square corresponding to the green paper, and a small green square in the centre corresponding to the small grey square, it will be noticed that the rose rapidly encroaches on the green, which disappears, whilst a rapid whirlpool appearance is seen in the centre of the field of vision. This experiment would seem to support strongly the view of Hering that the rose colour is actually subjectively produced on account of the proximity to green. I hope, however, to show by a single experiment that this cannot be the explanation.

Let us consider the factors of the experiment when a grey patch upon a whitish-green ground is under observation: the objective light reflected from the grey patch differs from that on the green ground chiefly in containing less green, that is to say, the light is relatively and objectively rose-coloured in comparison with the whitish-green ground. The white light for this purpose may be divided into two portions, one of which is green and the other is a mixture of the remaining constituents of white light, which give rise to a sensation of rose. If a small portion of the common constituent

green be deducted from both the whitish green and the white the green will appear less saturated and the white will appear rose. In this case the white light will be objectively rose in comparison to the green. It will be seen, therefore, that there are two ways in which the two coloured surfaces may be objectively considered. If the green be considered of less saturation than it really is, that is to say, a whiter colour, then the white will be rose in comparison with it, but if the white be considered white then the green will be objectively of greater saturation in comparison with it.

A simple experiment which I have devised for the purpose decides this point. If, when the grey square is situated upon the larger green square, another square of white paper of a size midway between the two other squares have a hole corresponding to the size of the small grey square cut in it, on laying this white paper so that the opening corresponds with the grey paper, the grey square will be seen without a trace of colour. A mark should then be made on the extreme left of the grey paper, and whilst one eye is kept rigidly fixed upon this spot the white square is gradually moved to the left until the field is occupied half by the whitish-green ground and half by the grey ground. It will be noticed that the green is greatly increased in saturation, and that not a trace of rose is visible upon the grey ground. If the right eye be kept fixedly upon these two surfaces for ten seconds, and then be directed to a white surface, a brilliant rose-coloured after-image much brighter and

more saturated than the one that was previously visible, and a pale white after-image, without a trace of colour corresponding to the grey region, will be seen. If the colour were really subjectively produced in the retina it should appear in this experiment as in the other. It might be thought that the increased saturation noticed in the green was due to the luminosity contrast of the white paper, but exactly the same result may be obtained with black paper, the green when uncovered appearing much more saturated and the subsequent after-image formed on the white ground is rose colour for the green portion and dark grey for the white portion. In this case, as with white paper, not a trace of green is seen in the after-image of the grey.

A simple experiment described by Waller [1] illustrates this relativity of perception very well. If a strip of grey paper be placed upon a sheet of white paper, and then a piece of green paper be placed on either side of the middle third of the grey paper, and the whole covered with a piece of tissue paper, no contrast colour or very little will be visible. If, now, the middle third of the strip of grey paper be isolated by means of two pins placed transversely, the middle third becomes strongly tinged with the contrast colour, rose. On repeating this experiment I find that, when the grey strip is seen as grey, the after-image is also grey, but when it is seen as rose, the after-image is green, and the rose after-image of the green appears less saturated. Also, when the

[1] *Journal of Phys.*, 1891, p. 44.

contrast colour is developed, the objective green appears less saturated than when the grey strip appears grey.

A definite amount of saturation is necessary before a colour can be recognised. This colour becomes much more marked on contrast. A tinted paper which appears pure white without comparison may, when laid on a pure white surface, appear very definitely coloured. If a square of cream-coloured paper be placed on a white ground, it will appear of a decided pale yellow; the colour of the white ground will, however, not be altered.

If the after-image of this paper on a white surface be examined it will appear as a pale blue square on a white ground, but no adjacent yellow is to be seen. The estimation of colour is always relative; for instance, if a pale yellow diamond be given to a man, who has to classify diamonds, as a standard white, he will classify the pure white diamonds as blue, and not sufficiently estimate the amount of yellow in those diamonds which are yellow. If a monochromatic region be examined with a double-image prism, so that the red side of one image be adjacent to the violet side of the other, no difference will be detected. Here we should expect that, if any colour induction were produced an immediate difference would be observable between lights which are objectively so different.

In examining the two images, the greatest care should be taken to have them both of the same apparent luminosity. It will be noticed that, when the images are of different luminosity, the hue is also different.

Both images appear monochromatic in themselves, but different in hue and luminosity. This is particularly noticeable in the blue-green region of the spectrum, as this is one of the portions of the spectrum in which the monochromatic divisions possess the fewest wave-lengths. The images are, however, larger because of the increased separation of the wave-lengths in this region. When viewed with the double-image prism, a monochromatic division shows two monochromatic images side by side, and exactly similar in every respect when the intensity of both is similar, but, if the intensity of one be greater than that of the other, one will appear definitely blue and the other definitely green.

This method is one which enables us to study very accurately the effects of simultaneous contrast. A monochromatic region can be viewed with the double-image prism, so that it appears as two images with a small space between. One of the shutters of the spectrometer can be moved, so that the two images increase in size and just touch. It will be noticed that the effect of contrast is most apparent at the edges—for instance, if a yellow region be observed, one edge appears green and the other adjacent edge appears orange. The whole of the image appears to be altered, that is to say, the image at which the orange edge is seen appears to be more yellow throughout, and the green one more green throughout. Each appears as if it were moved further from the other in the spectral range. We can, however, make the same wave-length appear as different

colours in the following way: If a monochromatic region be isolated, for instance, yellow, no difference being detected, the whole of the wave-lengths occupying this region appear yellow. If, however, we take the wave-length occupying the central position of the region and move the shutter on the green side until it occupies this central position, we can then move the shutter on the red side until a fresh monochromatic region is observed. This appears absolutely uniform in colour, but the colour appears orange-yellow instead of yellow, including that portion that was previously seen as yellow. We can now move the shutter on the red side till it occupies the centre of the first mentioned yellow region, and then extending the shutter on the green side, form a fresh monochromatic region. The colour will appear absolutely uniform as before, but it has now changed, and the whole has become greenish-yellow.

The contrast colour is most developed when the surface on which it is seen is small and situated on a large surface of very pale colour, which it is difficult to recognise as coloured without special comparison with a known white surface, as, for instance, if a small piece of grey paper be placed upon a large piece of very pale green paper. If the paper be regarded as white, the light reflected from the grey paper must be regarded as rose, for the subtraction of the small quantity of the green light from the light of the pale green paper in order to make this white is sufficient, when subtracted from the white light reflected from the grey paper, to make

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this appear rose. When it is recognised that the green paper is not white the contrast colour disappears, and the grey paper is seen as grey. The contrast colour is most developed on grey paper, and not nearly so well, if at all, on white or black paper. It is therefore produced in exactly those conditions in which the subtraction of a small quantity of green light will be most effective in altering the appearance of the colour. It is well known that in most contrast experiments, if a direct comparison be made with a known white surface, the contrast colour disappears. There is no reason why this should occur if the contrast colour were an actually induced colour.

There is an experiment of Hering which appears in many text books as conclusive evidence that the colour seen in simultaneous contrast is due to a definite retinal process distinct from direct stimulation by light. A grey stripe is situated at the bottom of a box. At a point slightly nearer the observer there is a small knob. This knob is viewed with the right eye through a red glass and with the left eye through a blue glass. Two distinct images are seen of the grey stripe; whilst the red and blue will blend into a purple more or less complete each image will appear of a complementary colour to that on the side on which it is situated.

As a matter of fact, quite an opposite conclusion ought to be drawn from this experiment, as the fact that the images do not fall on corresponding points of the two retinae has been overlooked. The corresponding

points of the other retina to the image on the blue side are stimulated by red light whilst those corresponding to the image on the red side are stimulated by blue light so that there is no reason why they should both appear complementary to purple. On my theory of colour vision they should appear the colours which are actually seen. For instance, if we take the image seen through the blue glass and which appears yellow, it appears yellow because the white light reflected from the front of the glass is relatively yellow in comparison to the light which is coming through the blue glass. White light may be considered as blue light plus the remaining rays which together make a yellow. If, therefore, the colours seen in simultaneous contrast be due to the exaggerated perception of relative difference, the white light should appear yellow. The colour seen is reddish-yellow on account of the red light falling on the corresponding points of the other retina. When this experiment is repeated so that no light is reflected from the front of the coloured glasses the image seen with the right eye through the red glass appears blue and that with the left eye through the blue glass red. If there be no white light reflected from the front of a coloured glass and the image be viewed with one eye only, it will appear black. This shows conclusively that the contrast colour is due to the white light and is not induced in the retina.

The following simple experiment shows that the colour in simultaneous contrast is due to the perception

of relative difference and not to the induction of colour in a region of the retina which is not stimulated. If coloured light be projected by a lantern on to a white screen and a small opaque object be placed so that a shadow is thrown upon the screen, no colour will be seen in this shadow unless stray light be reflected by the portion of the screen occupied by the shadow. If now the region of the screen in which the shadow is situated be illuminated by another light it will appear coloured and the colour which differs most relatively from that surrounding it. If a piece of black velvet be placed in the centre of the colour on the screen it will still appear black without a trace of the complementary colour. A small amount of coloured light may be reflected from the black velvet but this can be eliminated by making a shadow coincide with the black velvet.

My conclusion, therefore, is that the contrast colour developed in simultaneous contrast is due to the perception of an actual objective relative difference—in fact, the greatest difference which is perceptible in the circumstances, white being not a fixed objective quality, but a sensation produced by admixture of light of certain wave-lengths. If the sensation of one colour induce that of the complementary in the adjacent portion of the retina, there are many circumstances in which the colour ought to be visible and yet is not found. I have never yet, for instance (excluding negative after-images), seen the faintest trace of green on the dark surfaces in a photographic dark room illuminated by a pure red light.

Neither have I come across any other person who has seen green in these circumstances. On coming out of the dark room white objects appear only slightly tinged with green, if any change be noticed at all. Not the faintest trace of green is to be seen round red lights at night, and I find the greatest difficulty in obtaining an after-image even by staring fixedly at the red light, if this be not of considerable intensity.

The subject of induction of colour by simultaneous contrast can be investigated in another way, that is by entirely eliminating red or any other spectral colour and then studying the effects of simultaneous contrast. This may be accomplished by viewing objects through coloured glasses which are opaque to light of certain wave-lengths. In the case of red light we can use blue-green glasses, which are impermeable to the red rays. I have, therefore, had a pair of spectacles glazed with blue-green glass. This blue-green glass is absolutely opaque to the red rays from the termination of the spectrum to $\lambda 646$. There is considerable absorption from $\lambda 646$ to $\lambda 588$. The yellow rays are partially obstructed, whilst the glass is practically transparent to the green, blue, and violet rays. When objects are viewed through these spectacles not a trace of red is to be seen either directly or by contrast. An ordinary coal fire appears to consist of only yellow, or yellow-green flames, no orange or red being visible. The yellow light of the spectrum or a yellow object adjacent to a green one still appears yellow, and the colour appears

if anything to incline towards green rather than red. Reds appear black, or in a very bright light, and when they reflect orange rays, a dull brown. Yellow, green, blue, and violet can be seen, through the blue-green glasses. White objects at first appear blue-green, but after a short time again appear white. Objects corresponding to the dominant wave-length of the blue-green glass appear white or pale blue or pale green according to the composition of the colour. All contrasts are modified in a similar manner. For instance, a grey square on a green ground, in circumstances which give a bright rose contrast colour, appears pale blue through the blue-green glasses, and a grey on a blue ground yellow-green. No colour is seen the light of which cannot pass through the blue-green glass. Sir W. Ramsay, whose vision on my classification was trichromic (that is he describes the bright spectrum as consisting of red, red-green, green, green-violet, and violet), examined my series of contrasts through the blue-green glasses and in no instance called yellow red. He rather tended to call yellow yellow-green, or to use the term which he preferred, green with a very small amount of red in it. It would appear, therefore, that the exaggerated simultaneous contrast which I have found to be characteristic of these cases is not found in the absence of the objective exciting light.

These facts point to the conclusion that the sensation of red is not produced by simultaneous contrast in the absence of objective red light. They also support the

conclusion that yellow is a simple sensation and not compounded of a red and a green sensation. I can also find no evidence of the induction of colour by simultaneous contrast in the absence of objective light of that colour. Hartridge[1] gives facts indicating the exact position in the brain where simultaneous contrast takes place.

SUMMARY.

1. The colours seen by simultaneous contrast are due to the exaggerated perception of a real, objective, relative difference which exists in the light reflected from the two adjacent surfaces.

2. A certain difference of wave-length is necessary before simultaneous contrast produces any effect. This varies with different colours.

3. A change of intensity of the light of one colour may make evident a difference which is not perceptible when both colours are of the same luminosity.

4. Simultaneous contrast may cause the appearance of a colour which is not perceptible without comparison.

5. Both colours may be affected by simultaneous contrast, each colour appearing as if moved further from the other in the spectral range.

6. Only one colour may be affected by simultaneous contrast, as when a colour of low saturation is compared with white.

7. When a false estimation of the saturation or hue of a colour has been made the contrast colour is considered in relation to this false estimation. That is to say the missing (or added) colour is deducted from (or added to) both.

8. A complementary contrast colour does not appear in the absence of objective light of that colour.

9. The negative after-images of contrasted colours are complementary to the colours seen.

[1] *Journal of Physiol.*, 1915, p. 47.

CHAPTER XXVII.

SUCCESSIVE CONTRAST.

The term successive contrast is applied to the changes which are found when two colours are viewed successively in contradistinction to simultaneous contrast in which the colours are viewed side by side and at the same time.

Some of the phenomena of successive contrast are well known: for instance, if a piece of green cardboard be placed on a sheet of white paper and the observer regard it attentively for about 20 seconds and then suddenly withdraw it a pink image will be seen on the paper of the exact shape of the coloured cardboard.

The explanation of this pink after-image is that the retino-cerebral apparatus stimulated by the rays from the green paper has become more fatigued by these rays than that corresponding to the surrounding portions of the retina, therefore, when the piece of green cardboard is removed the white light coming from the portion of white paper corresponding to it appears to be deficient in green rays and so appears of the complementary colour.

The effects of successive contrast and the colours

of negative after-images are due to fatigue and the influence of surrounding regions. The portion of the white paper which appears pink, appears pink not because of the addition of pink to the white but because of the subtraction of green. If we place a piece of green cardboard upon a piece of pink paper and then after having viewed it for 20 seconds as mentioned above withdraw it, it will be noticed that the portion of the pink paper corresponding to the green will appear of a more saturated pink than the surrounding portions. This will be the case even when the green cardboard is of the same luminosity as the pink paper. The explanation of this is that there is a certain amount of green light reflected from the pink paper and as the portion of the retino-cerebral apparatus corresponding to this is fatigued to green light the portion of pink paper must appear more saturated. It is easy to demonstrate this green light in the light reflected from the pink paper. A small rectangular hole should be cut in a sheet of white paper, this should then be placed over the sheet of pink paper so that a small portion should be visible through the hole in the white paper or a small strip of the pink paper can be placed on a larger sheet of white paper. If this small pink strip be observed with the aid of a prism, it will be noticed that the pink strip will be spread out in the form of a spectrum, thus showing the constituents of the light reflected by the pink paper; the light reflected by any other coloured object may be analysed in the same way, very few

coloured objects reflect coloured light which is spectroscopically pure.

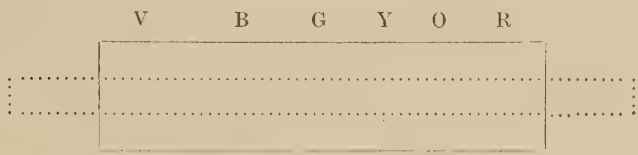
If, however, pure spectral light be used instead of the light reflected from coloured paper there is no increase in the saturation of a complementary colour after fatigue. Professor A. W. Porter and I[1] made a series of observations on negative after-images and successive contrast with pure spectral colours.

The greatest precautions were taken to prevent the admixture of stray light in those experiments which were of a crucial character.

In a dark room a horizontal spectrum as pure as possible was projected upon a screen. A portion of the retina of one eye was then fatigued by rigidly gazing at a portion of another horizontal spectrum which was isolated in the colour-perception spectrometer. The eyes were kept in a vertical position, that is, one over the other, so that the long axis of the after-image would be at right angles to the individual colours of the spectrum when the eye resumed its normal position. After the fatiguing light had been viewed for a period of about 20 seconds the eye was turned to the screen so that the after-image formed a band running right across the spectrum on the screen and occupying its centre. By this means any change either in colour or luminosity in the portion occupied by the after-image could be readily detected on account of the comparison with the colours of the unaltered spectrum seen above and below.

[1] *Proc. Royal Soc.*, B., vol. lxxxv., 1912, p. 434.

When the eye was fatigued with pure red light the following changes were noted in the region occupied by the after-image on the spectrum on the screen: the extreme red was slightly diminished; there was no perceptible action on the orange, yellow, or green. There was strong action on the blue and violet, these became much darker and bluer along the line of the after-image.



This experiment was repeated with two spectroscopes in order to exclude all stray light. A deep red glass only transparent to the red end of the spectrum was placed in front of the slit of one of the spectroscopes and a blue-green glass in front of the spectroscope in which the violet was isolated. The eye-pieces of the spectroscope were placed within two inches of each other and these eye-pieces and the head of the observer were enveloped in thick black velvet. The results were exactly the same as with the screen spectrum. The violet became much darker and bluer along the line of the after-image.

When orange was used as the fatiguing colour the dark blue after-image was seen right across the spectrum except in the region of the orange which appeared unaffected.

When orange-yellow was used a purple after-image

was seen right across the spectrum. The red was affected most. The general impression was that the band appeared as if painted over the spectrum. Yellow-green produced the same results, a purple after-image was seen similar to that caused by orange-yellow least affecting the orange. Blue-green produced a similar effect, orange least affected ; purple not red after-image. Blue produced a reddish purple after-image, no action on red and orange, the after-image seen over the rest of the spectrum. Blue of shorter wave-length 445 to 455 gave rise to an orange after-image, the violet and blue cut off and the green and red made yellower. The violet light caused a green after-image which made the violet and blue appear green and made the green appear slightly a yellower green and did little or nothing to red or orange.

Unless the fatiguing light were very bright no change was seen in yellow after fatigue to red or green.

When a monochromatic region was selected in the spectrometer and the eye fatigued for 20 seconds in a vertical position, on assuming the normal position the after-image was seen to cross the region. No matter what portion of the spectrum was selected the after-image where it was seen to cross the spectral band was seen as a grey square.

In these experiments the intensity of the light is of paramount importance. The after-image appears to be super-imposed upon the image formed by subsequent stimulation by light.

CHAPTER XXVIII.

COLOUR ADAPTATION.

In dark adaptation there is a considerable effect which takes place immediately on entering a dark room but which increases with the length of stay and the degree of darkness, so is there a definite effect produced when a person enters a room illuminated by an artificial light having previously been in daylight. This effect which may be designated colour adaptation increases with the time during which the eyes are subjected to the adapting light. I have estimated the effect of colour adaptation in four ways. First: A dark room being illuminated by light of a certain wave-length, one eye is subjected to light of this wave-length, whilst the other is closed, and is therefore in a state of more or less dark adaptation. The dark room communicates with another dark room by a door in which a hole is pierced to allow the passage of the eyepiece of my spectrometer. A certain region of the spectrum is isolated in my spectrometer and after the stated period this is examined first by the eye which has been exposed to the light and then with the eye which has been covered up. The same spectral region is also observed

after both eyes have been subjected to the adapting light.

The second method consists of wearing a pair of spectacles glazed with coloured glass and noticing the changes which appear in coloured objects viewed through these glasses for a longer or shorter period. No light is allowed to enter the eye except through the coloured glasses. As the composition of the light which passes through the glasses is known, those changes which are due to the absorption of light by the coloured glass can be separated from those which cannot be accounted for in this way. Definite spectral regions are examined first immediately after putting on the glasses and then again after a longer period.

The third method is to note the changes which appear in coloured objects in a room illuminated by light of known composition, which cannot be explained by the character of the light.

The fourth method is comparing the appearance of colours in a photometer, one colour being illuminated by daylight and the other by artificial or coloured light. The objects are then examined first by daylight and then by the artificial light which has been used. The difference between the results obtained in this way and those of the photometer represents the effects of colour adaptation. The same colours are also examined in the photometer, both sides being illuminated first by daylight and then by artificial light.

When a spectrum is examined after the eyes have

been exposed for twenty minutes in a room illuminated only by sodium light, the yellow appears to have disappeared from the spectrum. The red and green appear to meet without any intermediate colours and the red, orange, and green have lost any yellow character which they previously possessed. There is no increase in the blue or violet and the red and green are not diminished. If, before exposing the eyes to the sodium light, a small portion of terminal red be selected, this is found to be just as visible after the exposure as before.

The same condition is found with artificial light in which the yellow rays predominate. Yellow is discriminated with difficulty from white by electric light. It is often impossible to detect a yellow stain on a white cloth by electric light which is very obvious and marked by daylight.

When blue-green spectacles are first put on all white objects appear a vivid blue-green. This blue-green gradually fades until in about ten minutes time a piece of white paper or white cloth appears absolutely white, without a trace of blue-green. In fact, though I know that blue-green light is falling upon the eyes, I can see no trace of this colour. This shows conclusively how very little the conscious judgment contributes to these results apart from the perception of relative difference. If the sky be white, misty and overcast, this will appear only faintly coloured blue-green; if it be much brighter or a naked filament of an electric light be looked at these are seen as blue-green. Black objects appear black

throughout. I have never been able to find the faintest tinge of red in a black object. When the spectacles are removed white objects appear a decided rose pink, and a perceptible interval elapses before objects regain their normal colour.

I found that I could read all Stilling's pseudo-isochromatic tables for testing for colour blindness with the blue-green spectacles on. An examination of the spectrum immediately after putting on the blue-green spectacles showed that there was no red to be seen, there was a small amount of orange and the yellow, green, blue, and violet were visible. After wearing the glasses for about ten minutes until white appeared white and then again examining the spectrum there was no marked change in the orange or any other part with the exception of the green which looked paler and more yellow. I picked out the yellow of the spectrum by means of the shutters of the spectrometer at exactly the same wave-lengths with and without the blue-green spectacles and with shorter and longer periods of colour adaptation. The sodium flame appears less red through the blue green glasses and there is no change to red after there has been colour adaptation. This shows conclusively that yellow is a simple sensation and not compounded of red and green sensations. The results are in accordance with those of colour fatigue.[1] The experiments on colour adaptation with the sodium light and the subsequent disappearance of yellow from the spectrum

[1] *Proc. of the Royal Soc.*, B., vol. lxxxv, 1912, p. 434.

show that the yellow sensation is stimulated by the green, orange, and red rays as well as by the yellow. This is in accordance with the facts of colour mixing, and explains why red and green light make a yellow when mixed.

An examination of definite regions in the green isolated in my spectrometer shows that the region corresponding to the dominant wave-length of the glasses is most affected, the regions on the blue side and the yellow side appear bluer and yellower respectively.

The following coloured cards were used for comparison in the photometer.

Colour by daylight.	*Colour by osram electric light.*
1. Yellow.	Pale orange.
2. Orange.	Orange.
3. Slate.	Grey.
4. Blue.	Blue.
5. Yellow-green.	Yellow-green.
6. Green.	Green.
7. Brown.	Light brown.
8. Dark green.	Greenish black.
9. Olive green.	Dark green.
10. Yellow.	Yellow.
11. Orange-yellow.	Orange-yellow.
12. Chocolate brown.	Terra cotta brown.
13. Blue.	Saturated ultramarine blue.
14. Brown.	Chocolate brown.
15. Dark slate.	Dark grey.
16. Rose red.	Red.
17. Rose.	Rose.
18. Orange.	Orange.
19. Black.	Black.
20. Brown.	Brown.

It will be noticed that there is very little difference in the appearance of the colours by daylight and by electric light. This is due to colour adaptation. If, however, two cards of the same colour be placed in a simple photometer which I have had constructed for the purpose and one side be illuminated by daylight and the other side by an osram electric light the difference is very striking. The eye which examines the colours in the instrument has previously been in a state of daylight adaptation. It will now be found that 13 blue illuminated by electric light almost exactly matches 12 brown illuminated by daylight.

The following shows the changes in the appearance of the colours of the previously mentioned cards, when two exactly similar cards are illuminated in the photometer on the one side by daylight and on the other by osram electric light. The eye used is daylight adapted.

Illuminated by daylight.	*Illuminated by electric light.*
1. Greenish-yellow.	Orange.
2. Brown.	Orange.
3. Slate.	Brown.
4. Blue.	Grey.
5. Green.	Yellow.
6. Green.	Greenish-yellow.
7. Brown.	Orange.
8. Green.	Yellow-green.
9. Pure green.	Dark yellow.
10. Greenish-yellow.	Orange.
11. Greenish-yellow.	Orange.
12. Chocolate.	Orange.
13. Blue.	Purplish-black.

14. Brown.	Orange.
15. Slate.	Brown.
16. Rose red.	Scarlet.
17. Rose.	Orange.
18. Brown.	Yellowish-orange.
19. Blue-grey.	Yellow-brown.
20. Brown.	Orange.

It will be seen that colour adaptation greatly assists the correct discrimination of colours.

The same cards were now examined in exactly the same physical conditions, that is to say, two exactly similar cards were placed in the photometer and one

Illuminated by daylight.	*Illuminated by electric light.*
1. Green.	Orange-yellow.
2. Buff.	Orange.
3. Blue.	Grey.
4. Bright blue.	Blue-grey.
5. Green.	Yellow-green.
6. Blue-green.	Yellow-green.
7. Grey.	Pale orange.
8. Blue.	Black.
9. Green.	Yellow-green.
10. Yellow-green.	Orange-yellow.
11. Greenish-yellow.	Orange-yellow.
12. Purple-brown.	Orange.
13. Bright blue.	Dark blue.
14. Grey.	Brown.
15. Slate.	Grey.
16. Rose.	Red.
17. Purple.	Orange.
18. Purple-brown.	Orange.
19. Blue-black.	Black.
20. Grey.	Light brown.

side was illuminated by daylight and the other by electric light. The eye used for viewing the cards was electric light adapted by viewing white paper illuminated by electric light (Osram incandescent) for from 5 to 10 seconds. The cards used were the same as before.

When a match had been made to the daylight adapted eye of chocolate brown 12 illuminated by daylight and blue 13 illuminated by electric light, and this was viewed with an electric light adapted eye, the two no longer matched, the blue now appeared blue and the brown pale purple.

No colour is seen by colour adaptation the appropriate physical stimuli of which are not present in the adapting light. On remaining in a room illuminated by light through red glass windows green will become increasingly noticeable but only when a certain amount of green light is transmitted by the red glass. If, however, a red glass be used which is impervious to green, not a trace of green will be seen in green or black objects.

Colour adaptation appears to produce its effect by subtraction and not by the addition of any fresh colour which is not previously present. The ultramarine blue which when illuminated by electric light matches a chocolate brown illuminated by daylight appears blue after colour adaptation with electric light through the subtraction of the yellow element of the light reflected from the card. A blue sky appears much bluer when viewed from a room illuminated by electric light, than

it does when seen from an unlighted street, because when viewed in the latter position the eyes are adapted for the light of the sky and when viewed from the room any yellow element is subtracted.

Summary.

1. In colour adaptation the retino-cerebral apparatus appears to become less and less sensitive to the colour corresponding to the dominant wave-length and to set up a new system of differentiation.

2. When light of a composition differing from that of daylight is employed to illuminate objects an immediate and unconscious estimation of the colours of these objects is made in relation to this light, the light employed being considered as white light.

3. No colour is seen of which the physical basis is not present in the light employed.

4. When spectral regions are examined with a colour adapted eye, that of the dominant wave-length appears colourless whilst those immediately on either side of it appear to be shifted higher and lower in the scale respectively.

5. There is immediate colour adaptation as well as colour adaptation after a longer stimulation with the adapting light.

6. Colours which correspond to the dominant wave-length of an artificial light are with difficulty discriminated from white by this light.

7. Colour adaptation may bring two colours below the threshold of discrimination, then the two appear exactly alike when by another light a difference is plainly visible.

8. Colour adaptation increases the perception of relative difference for colours other than the dominant.

9. The conscious judgment has very little effect in colour adaptation.

10. Colour adaptation greatly helps in the correct discrimination of colours and masks the very great physical differences which are found with different kinds of illumination.

11. Yellow after colour adaptation to green still appears yellow and not red.

12. Colour adaptation appears to produce its effects by fatigue for the dominant colour not by directly increasing the effect of its complementary. Spectral blue does not appear brighter after colour adaptation to yellow.

CHAPTER XXIX.

THE THEORY OF COLOUR VISION.

A ray of light impinging on the retina liberates the visual purple from the rods, and a photograph is formed. The rods are concerned only with the formation and distribution of the visual purple, not with the conveyance of light impulses to the brain. The ends of the cones are stimulated through the photo-chemical decomposition of the visual purple by light, and a visual impulse is set up which is conveyed through the optic-nerve fibres to the brain. The character of the stimulus and impulse differs according to the wave-length of the light causing it. In the impulse itself, we have the physiological basis of the sensation of light, and in the quality of the impulse the physiological basis of the sensation of colour. The impulse being conveyed along the optic-nerve to the brain, stimulates the visual centre, causing a sensation of light, and then, passing on to the colour-perceiving centre, causes a sensation of colour. But though the impulses vary in colour according to the wave-length of the light causing them, the retino-cerebral apparatus is not able to distinguish between the character of adjacent stimuli, not being sufficiently

developed for the purpose. At most, seven distinct colours are seen, whilst others see in proportion to the development of their colour-perceiving centres, only six, five, four, three, two, or none. This causes colour blindness, the person seeing only two or three colours instead of the normal six, putting colours together as alike which are seen by the normal sighted to be different. In the degree of colour blindness just preceding total, only the colours at the extremes of the spectrum are recognised as different, the remainder of the spectrum appearing grey.

It is obvious that this theory could not be true if the facts of colour-vision were as stated in the books of twenty-five years ago. Apart from the relative functions of the rods and cones, if colour vision were a secondarily developed power of discrimination, then the following should be facts :

1. There should be innumerable varieties of colour discrimination, which could be arranged in a series from total colour blindness to super-normal colour-vision.

2. The number of colours seen in the spectrum should depend upon the development of colour discrimination ; those colours presenting the greatest physiological difference being the first to be discriminated.

3. The physiological difference would probably correspond roughly to the physical difference ; that is to say, the largest and smallest waves would be the first to be differentiated.

4. Yellow should be a simple but secondary sensation.

5. A pure spectrum should be divisible into a series of monochromatic areas, the size of these areas depending upon the development of colour discrimination.

6. There should be defects of light perception distinct from defects of colour perception, shortening of the red or violet end of the spectrum should be distinct defects, and not necessarily associated with defective colour discrimination.

7. There should be innumerable varieties of dichromic vision.

8. There should be trichromic cases of defective colour perception, three colours being seen in the bright spectrum, yellow being seen as red-green, and blue as green-violet.

9. All colours when reduced sufficiently in luminosity and area should appear white, the colour disappearing first in the least developed portions of the retina.

10. Simultaneous and successive contrast should be increased in those with defective colour discrimination.

11. Those with defective colour discrimination should see like those with better discrimination in conditions of more difficulty.

Now all these predictions have been fulfilled, and are found to be actual facts, so that whilst the facts support the theory, they present difficulties to be solved by any other theory.

The theory may be put clearly in another way. All physical stimuli which affect the sense organs can be arranged in a series. Physical series agree in their ill-

defined character. For instance, let us consider a time series. It is impossible to conceive how there could be a commencement to time, or that time can ever end, or that we can conceive a portion of time, however small, which cannot be subdivided; thus the portion of time which light takes to pass through the space of an inch can be divided into millionths.

A dispersed ray of sunlight constitutes an almost perfect physical series. The sensations of colour which it calls forth are due to the difference in the wave-lengths of its vibrations. Those vibrations which excite the sensation of red are the longest, and are placed at one end of the spectrum; while those which call forth that of violet are the shortest, and are placed at the opposite end of the spectrum. There are vibrations beyond these points which excite neither the sensation of light nor that of colour, and hence fail to be perceived through the sense of vision.

Whilst the physical series has no definite commencement, termination or unit the psycho-physical series, that is, the physical series as it appears to the mind, has a definite commencement, a definite termination, and a definite unit. The absolute psycho-physical units, the monochromatic divisions, are the physiological units of discrimination in the conditions in which the experiment is made; the definite colours seen in the spectrum may be called approximate psycho-physical units. It will be seen that this theory is in complete accordance with all the facts of colour-vision.

CHAPTER XXX.

OBJECTIONS TO OTHER THEORIES OF VISION AND COLOUR VISION.

It must be obvious to the reader that the facts given in the preceding chapters are quite inconsistent with the older theories of vision and colour vision. These theories have been largely built up on misstatement and defective methods. None of the objections given have been answered. Classifications have been made in accordance with the theories which are quite inconsistent with the facts, and modifications of the theories made to explain particular cases at once give rise to difficulties in the explanation of other cases. All fundamental observations should be made with pure spectral light, as the use of coloured wools, coloured papers and pigments gives rise to results which are entirely different and due to the defects of the methods employed. There has always been a belief that there are definite fundamental colour sensations, and when red, yellow, and blue were disproved the three fundamental sensations of the trichromatic theory were based on the facts of colour mixing. Though it was founded on the facts of colour mixing, there are many facts of colour mixing

which the trichromatic theory will not satisfactorily explain. For instance, a considerable amount of one spectral colour may be added to another without altering its appearance. Houstoun has clearly shown that from a mathematical and physical point of view, only one substance is necessary and that there is no evidence of more than one.

A consideration of the facts which I have given shows that neither the Young-Helmholtz nor Hering's theory will explain the phenomena of colour-vision in a satisfactory manner. I shall not deal with any other theories, because the same objections which may be made against the two main theories are equally applicable to the modifications, and the more modern theories are either strikingly similar to mine or combinations of mine with one or both of the older theories.

I. Vision.

1. There is no qualitative difference between the foveal and para-foveal regions. This fact is strongly against the view that the rods are percipient elements in the same way as the cones, possessing a qualitative difference in their perception.

IIA. Normal Colour Vision. (Young-Helmholtz theory.)

1. *Colour Fatigue.* Many forget that the trichromatic theory was devised in order to explain the facts of colour mixing. What we want is evidence that the assumptions **are true.** For instance, that simple yellow can be split

up into its hypothetical red and green. This cannot be done. An hour's dark adaptation does not alter the hue of spectral yellow. Fatiguing the eye for blue does not alter the hue of spectral yellow. As blue is supposed to be made up chiefly of the green and violet sensations, and yellow to be made chiefly of red and green sensations, the green element should be affected after fatigue with blue, and yellow viewed subsequently should appear red. This is not the case. Unless the fatigue be excessive, spectral yellow does not appear red after fatigue with green or green after fatigue with red. The eye may also be fatigued with spectral yellow, so that all yellow disappears from the spectrum without affecting the appearance of a very feeble red.

2. *Simultaneous and Successive Contrast.* The theory will not explain the facts of simultaneous and successive contrast.

3. *After-Images.* The study of these phenomena show that the theory must be interpreted in a sense of three photo-chemical substances which act upon one and the same cone. This modification has been adopted by most authorities; these photo-chemical substances, however, must be outside the cone and not within it, for in no other way can we explain how a blue after-image can move across the field of vision and in fact pass right through a yellow after-image formed by another object. The formation of a negative after-image in the dark is not well explained according to this theory. If the theory were true the negative after-image should change colour

as it fades away, because the sensation which was least fatigued would recover first; this is not the case.

4. *Colour Adaptation.* The facts of colour adaptation are quite inexplicable on this theory. For instance, spectral yellow after colour adaptation to green, should appear red, but it still appears yellow.

5. *Hue Perception.* No explanation is given of the fact that when a certain portion of the spectrum is isolated it appears monochromatic.

6. *Evolution.* The theory is not in agreement with evolution.

IIB. Colour Blindness. (Young-Helmholtz.)

1. *Hue Perception.* The theory does not explain why there should be a defect of hue perception in those who have lost one of their sensations. It is this defective power of hue differentiation which causes colour blindness. There is no reason why a man with only two sensations should be defective in hue differentiation. It is true that he would have a different colour perception from the normal which would be elucidated by special methods of research, but the theory gives no explanation why red should be confused with green, because a different amount of the two sensations is stimulated in each case. It is for this reason that those dichromics bordering on the trichromics are able to pass so many tests. Still more does the theory fail to explain the defective hue-perception of those whom I have designated trichromic, tetrachromic, and pentachromic.

2. *Perception of Luminosity.* The theory does not explain why many dichromics have a luminosity curve similar to the normal.

3. There are not two or three definite varieties of colour blindness, as there should be according to the theory.

4. The theory does not account for the shortening of the red end of the spectrum, which is found in cases in which there is no defective hue perception. The same applies to the shortening of the violet end of the spectrum.

5. The theory will not explain why simultaneous and successive contrast are increased in the colour blind.

6. *The mistakes made by the colour blind.* The theory will not explain the mistakes of the colour blind. In many cases defects of light perception have been given as the cause of defects of colour perception. How could the loss of half of a hypothetical green sensation cause dichromatism? How is it that so many colour blind are able to pass so many matching tests, including the Holmgren test? A tetrachromic will pick out all the green beads in my bead test, but do it in a very characteristic manner. It is evident that he does not see the difference between the colours which is evident to the normal sighted. If the Young-Helmholtz theory were true, there should be an entirely new system of colours for the colour blind, depending upon the amount of the sensations present.

7. *Other Tests.* There are numerous other facts which are inconsistent with the theory. How, for

instance, can a bad dichromic be explained on the view that he is partially defective in one of his sensations? Again, in trichromic cases with shortening of the red end of the spectrum, the region selected as pure yellow is shifted towards the violet end of the spectrum, being in the yellow-green of the normal sighted. On the Young-Helmholtz theory, the red sensation being smaller, the green should advance on the red as the curves would cut nearer the red end, so the yellow should in these cases be nearer the red, not nearer the green.

A. Normal Colour Vision. (Hering's Theory.)

This theory explains the facts of normal colour vision far better than the Young-Helmholtz. There are, however, two ways of looking at the subject. Hering assumes that the colours seen in simultaneous and successive contrast are due to the development of colour on account of the previous excitation. All the facts, however, can be explained on the assumption that the colour is subtracted from the region under observation, instead of its complementary being added. For instance, if a white object appears blue after viewing a yellow one, the blue appears not because blue is developed at that spot, but because the cerebro-retinal apparatus has become fatigued for the yellow rays and so these being subtracted from the white the resulting mixture appears blue. I can find no evidence of a colour being developed in the absence of the physical stimuli which usually

cause it. Spectral blue, for instance, is not increased, but diminished after fatigue for spectral yellow. An exception should perhaps be made to an after-image which is seen in the dark. This, however, is certainly due to modifications of the Eigenlicht caused by photo-chemical substances present in the retina. Instead, however, of the after-image being easier to produce, as it should be, according to this theory, after a prolonged stay in a dark room, it is much more difficult. In fact, after fatigue with red light of gradually increasing duration, the blue-green after-image not only becomes more and more difficult to produce and more evanescent, but a red star is seen in its centre, which gradually increases in size with succeeding experiments.

Colour adaptation cannot be explained on this theory as the results are plainly due to subtraction of the colour of the dominant light.

B. Colour Blindness.

The facts of colour blindness are explained very inefficiently by this theory. For instance, a trichromic case cannot be explained at all.

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